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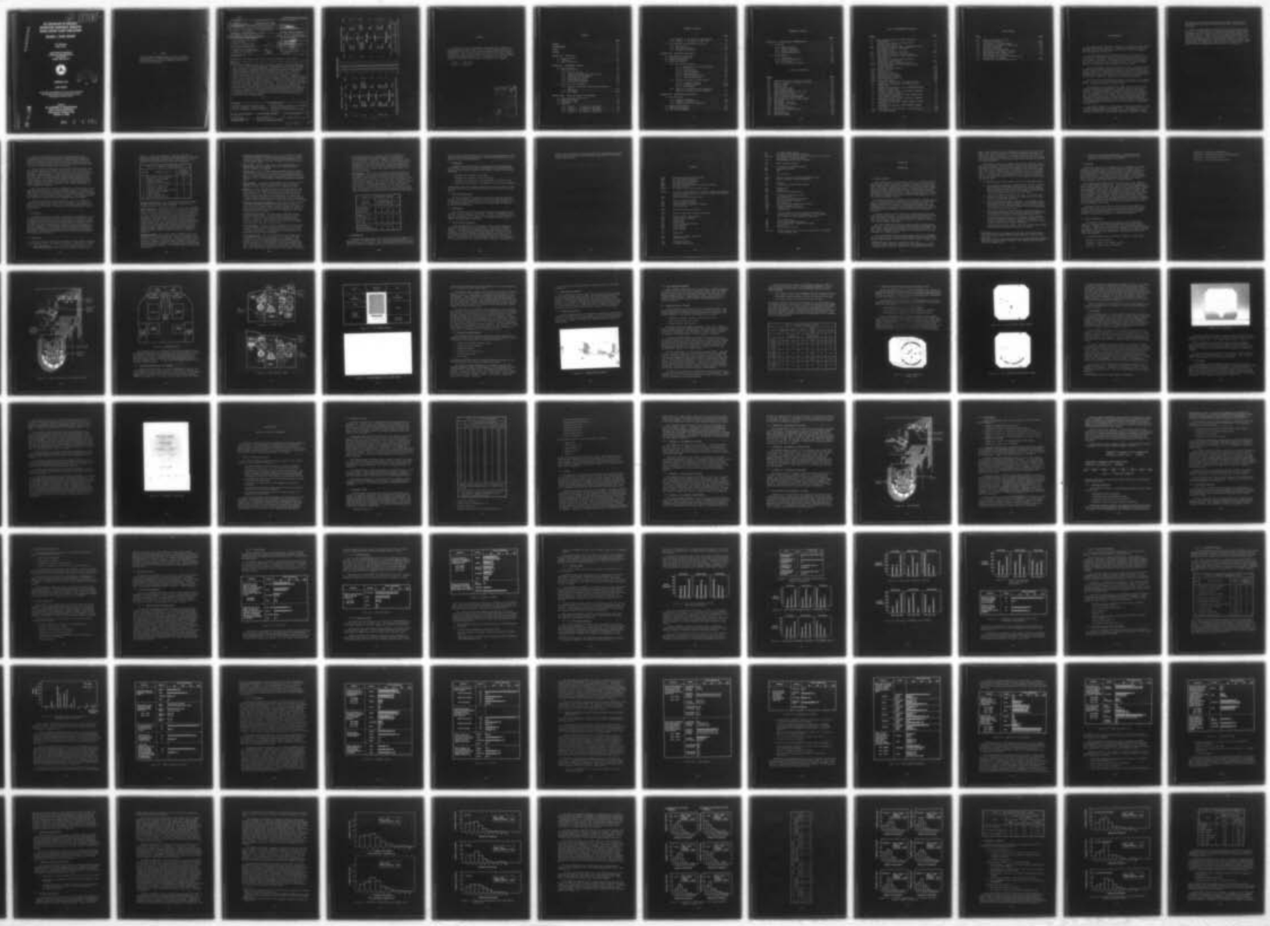

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AN EVALUATION OF AIRCRAFT SEPARATION ASSURANCE CONCEPTS USING AIRLINE FLIGHT SIMULATORS

VOLUME I: STUDY REPORT

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NOVEMBER 1979

FINAL REPORT

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Vol-2

16. Abstract
This report documents an evaluation of Aircraft Separation Assurance (ASA) concepts using an airline flight simulator. The primary objective of the experiment was to determine the cockpit information requirements for an aircraft collision avoidance system. Qualified pilots from commercial aviation and industry flew typical operational scenarios in the simulated Los Angeles area. During the flight, conflict situations with other aircraft developed, and pilots were asked to respond to these situations on the basis of information presented to them by one of three experimental collision avoidance displays. Computer-collected data on pilot response to collision avoidance commands and resultant miss distances were correlated with data from questionnaires filled out by participating pilots to determine the cockpit information requirements. The subjective comments addressed the areas of required display information items, use of color, audible alert, symbols, workload, pilot confidence in the system, and pilot display preference. Altitude, range, relative bearing, and other-aircraft heading have been identified as the most important and most essential information elements in the resolution of potential conflicts. The report provides a statistical analysis of the accumulated data and includes recommendations for the development and operational implementation of the ASA program.

17. Key Words
Aircraft Separation Assurance; ASA; Collision Avoidance; Cockpit Displays; Airline Simulators; Air Traffic Control

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METRIC CONVERSION FACTORS

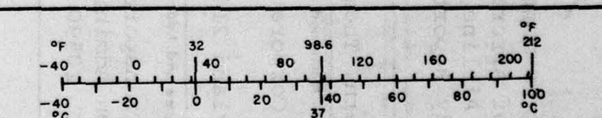
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, *Units of Weights and Measures*, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

A study of the cockpit information requirements for an airborne collision avoidance system has been conducted for the Systems Research and Development Service of the Federal Aviation Administration under Contract DOT-FA78-4091. This report documents the results of this study. Further experimentation and operational flight tests with specific Aircraft Separation Assurance System equipment should be conducted to confirm these findings. The results of this study are presented in two volumes.

Volume I - Study Report

Volume II - Appendixes

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ACKNOWLEDGMENTS

The success of this experiment reflects the contribution of many people from many organizations. While it is impossible to acknowledge each one, some made such major contributions that this report would be incomplete without recognition of their work.

First, we acknowledge the contribution made by the 74 pilots who served as test subjects and the many other pilots who volunteered to serve but could not be scheduled. These test subjects came on their own time, in the middle of the winter, and endured four hard hours in the middle of the night to further the cause of aviation safety. This report is based wholly on the performance and contributions of these pilots.

At the Air Transport Association of America, Frank C. White and William M. Russell coordinated the advisory functions of the Flight Systems Integration Committee and Communications Committee through the Joint Separation Assurance Task Force. This task force, with cochairmen Bill Herndon of Pan American World Airways and Harold Fink of Delta Air Lines, provided valuable guidance on scenarios, display types, and flight procedures.

The Air Line Pilots Association recruited the majority of the volunteer pilots. The success of this recruitment effort is the result of the work of E.V. Fretwell and William B. Cotton of ALPA.

The personnel at the United Airlines Flight Training Center enthusiastically supported this experiment. Fred Mohr served as the project coordinator, arranging schedules, administrative support, and personnel support. Jim Ungry provided corporate-level liasion support for the project. The simulator services section, under the direction of Dale Seay, made the modifications to the simulator and provided maintenance support throughout the experiment period. Mike Sangster provided exceptional engineering support, assisting with the test bed integration and providing the necessary software modifications to the visual system to incorporate scenario traffic.

Our special thanks go to the personnel at Litton Aero Products -- Dave Bjorndahl, LeRoy Singleton, and Richard John -- who supplied, at no cost, the light emitting diode (LED) displays used in this experiment. They developed and packaged the LED displays, developed a compatible interface,

and supported the displays throughout the experiment. These displays allowed the pilots to evaluate the usability of this advanced display technology.

We wish to acknowledge the support of the FAA in execution of this experiment. We were fortunate to have Thomas Williamson, William Hyland, and Richard Bock monitoring this program for the Systems Research and Development Service. Thomas Imrich of the Flight Standards Service provided much appreciated comments on flight procedures and scenario content. The FAA Rocky Mountain Region assigned Chester MacMillan to assist in scenario development and act as the air traffic controller for all simulation sessions. Mr. MacMillan's application of air traffic control procedures contributed immeasurably to the realism of the simulation.

SUMMARY

1. INTRODUCTION

During December 1978 and January 1979, 74 pilots, representing 12 airlines, government agencies, and fleet operators, participated in a cockpit simulator evaluation of a generic collision avoidance system. This evaluation is part of the Federal Aviation Administration's (FAA) Aircraft Separation Assurance (ASA) Program.

The major objective of the evaluation was to determine the information requirements for an airborne collision avoidance system and to record and measure the responses of air carrier flight crews to a realistic simulation of potential midair collisions. An equally important objective of the program was to prove that a test bed using an airline cockpit simulator could be developed for evaluation of ASA concepts and systems. The successful completion of this program is proof of the achievement of this basic objective.

2. DESCRIPTION OF THE EXPERIMENT

A simulation test bed was set up at the United Airlines Flight Training Center in Denver, Colorado, using a Boeing 727 cockpit simulator that featured a computer-generated night visual scene. This system was modified so that other simulated aircraft would appear when their position relative to the simulator cockpit was within the forward windshield area. Figure S-1 illustrates the test-bed layout. A simulation control computer was interfaced to the simulator to provide an air traffic control (ATC) simulation environment. Progress was monitored and the simulation was controlled through interactive terminals. Pilots flew typical scenarios in the simulated Los Angeles area and were exposed to each of three different collision avoidance displays installed in the cockpit simulator. The selected ASA display devices included a modified Instantaneous Vertical Speed Indicator (IVSI), a Light Emitting Diode (LED) Display, and a Cathode Ray Tube (CRT) Display. The IVSI used lighted indicators to display only ASA commands. The LED display presented ASA commands and traffic advisories in alphanumeric form. The CRT display provided a graphical presentation of ASA commands and traffic advisories.

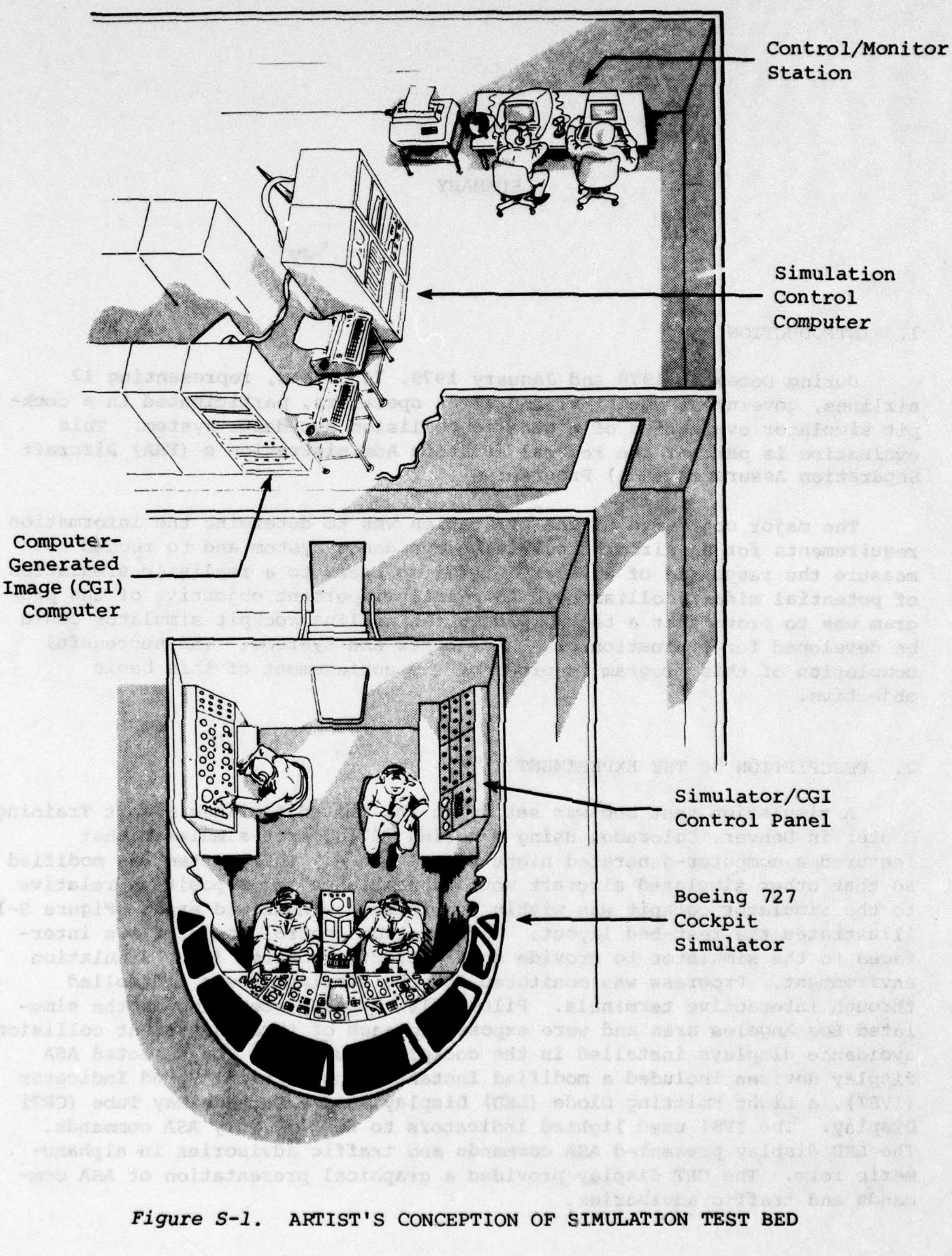

Figure S-1. ARTIST'S CONCEPTION OF SIMULATION TEST BED

Volunteer pilots, solicited from the aviation community, were provided with an advance briefing packet that described the experiment, the test bed setup, the test scenarios, and administrative information. Upon arrival at the test site, each crew received a formal briefing that reviewed the advance material and included a slide presentation and videotape on the collision avoidance system's displays.

The test session consisted of three scenarios that represented typical night flights departing Los Angeles International Airport for a nearby destination. The crew received a clearance from the air traffic controller and made a standard departure. Radio contact was maintained throughout the flight, which proceeded outbound for approximately 20 minutes, then was cleared back to Los Angeles airport along a route normally used for inbound traffic. The turnaround was explained in the preflight briefing and was therefore anticipated by the crew. Each flight consisted of all phases encountered during an operational flight: takeoff, departure, en route, approach, and landing.

During the flight, the crew was confronted with six preplanned collision situations that generally resulted in a commanded action. This action was shown with supporting traffic information on the appropriate collision avoidance display. Pilots were instructed (in the pre-flight briefing) to respond to the display by using standard aircraft maneuvers. The simulator was the only aircraft in the scenario that was equipped with an ASA system.

Data were collected on simulator position, velocity, and altitude; collision avoidance display status; and pilot response. In addition, subjective pilot comments were collected in a debriefing session immediately following each test session. The debriefing included completing a lengthy questionnaire.

3. DATA ANALYSIS

The data collected were analyzed to determine the acceptability of the Aircraft Separation Assurance concepts tested during the simulation session. The subjective data developed from the questionnaires and comments and the performance data derived from the recorded quantitative data were evaluated to develop the results and conclusions of this study. Qualitative data were used primarily to develop pilot reaction to questions of display readability, comprehension, color, format, information elements, information usefulness, and impact of the ASA function on flight and control procedures. Quantitative data provided measurements of pilot response to ASA commands and resulting miss distances.

4. CONCLUSIONS

The test subjects provided clear statements of their opinions regarding the ASA concepts tested. The significant results are summarized as follows:

- Information Elements. From a list of 11 potential collision avoidance information items, the test subjects rated 4 items as most

essential. None of the remaining 7 items were selected as essential by more than 21 percent of the test subjects. The items listed below the dashed dividing line in Table S-1 can be categorized as insignificant in the view of the respondents.

Table S-1. RANKING OF INFORMATION ITEMS

Rank	Information Item	Percent Responding "Essential"
1	Altitude of other aircraft	85
2	Range of other aircraft	81
3	Relative bearing	59
4	Heading of other aircraft	51
5	Horizontal closure rate	21
6	Vertical closure rate	17
7	Vertical speed of other aircraft	20
8	Projected miss distance	14
9	Closure angle	7
10	Other aircraft type	5
11	Other aircraft identity	3

- Altitude Representation. The overwhelming majority (89 percent) favored a mean sea level (MSL) or absolute representation of altitude versus a relative representation.

- Traffic Advisories. More than 79 percent of the pilots considered traffic advisories an essential part of an ASA display. The test subjects found that traffic advisories were useful in preventing a potential collision from developing or in resolving a potential collision. When the IVSI display was used, more collision avoidance commands resulted because of the lack of traffic advisory information. The traffic advisories were used to locate and identify other traffic. The test subjects preferred ASA-generated traffic advisories to those issued by air traffic controllers because of the continuous updating capability of ASA. This was beneficial in both acquiring the correct aircraft and keeping traffic in sight. However, pilots believed that a display of traffic advisories should be limited to the two or three most important.

- Display Preference. Of the three types of displays used in the experiment, the CRT display was most popular (49 percent of the subject pilots rated it number one). The other two displays, LED and IVSI, received an even share of the remaining votes. A significant point, however, is that more than 90 percent of the test subjects found their second choice acceptable and 73 percent found their third choice acceptable. Pilots feel strongly that something is needed now.

- Alternative Display Techniques. When pilots were asked to suggest alternative instruments that could be modified to display collision avoidance information, the most commonly recommended devices were the horizontal situation indicator (HSI/EHSI), the flight director, and the weather radar.

- Use of Color. The use of color aids in the interpretation of the traffic advisories and commands. The use of red for positive maneuver commands is acceptable.

- Audible Alert. There is almost complete agreement that an audible alert is required when the ASA system detects a potential conflict. There is a universal belief that there are already too many audible alarms in airline cockpits; however, the general feeling of the test subjects is that a life-threatening situation justifies an additional alarm.

- Use of Symbols. The pilots preferred symbols over text for positive commands if only one method of presentation could be provided. However, they had a clear preference for a combination of both.

- Workload. The test subjects believed that the introduction of ASA would result in an acceptable increase in the cockpit workload for the nonflying pilot. This increase would be greatest for the more complex displays that require close monitoring. The pilots also believed that the communications workload would increase because of a greater number of inquiries to ATC from flight crews to coordinate maneuvers resulting from conflicts and ASA-displayed traffic advisories.

- Horizontal Versus Vertical Maneuvers. There was no strong preference for either horizontal or vertical avoidance maneuvers during the climb, cruise, and descent phases of flight; however, the pilots preferred horizontal maneuvers during takeoff, approach, and landing. The passenger comfort factor was most often mentioned by those who preferred horizontal maneuvers.

- Excessive Maneuver Rates. The test subjects generally believed that they did not need to use unusual maneuver rates to resolve a conflict. Simulator position measurements confirmed that the majority of the pilots used standard turn and pitch rates during resolution maneuvers. Most banks were less than 30°, and maximum pitch rates were less than 2.5° per second.

- Pilot Confidence. The pilots expressed confidence in the capability of the ASA system to resolve potential conflicts. They felt more confident in underflying and overflying other aircraft with 1,000 feet separation; however, the majority believed that current IFR separation criteria should be retained.

- Pilot Response Time. The pilots considered their response time to be independent of the type of display in use; however, the IVSI produced the shortest average response time to commands (2.996 seconds), and the CRT displayed commands resulted in the longest average response time (3.468 seconds). The average response time for the LED display (3.123 seconds) was quite close to that of the IVSI. The difference was due to both the location of the CRT display and the more complex symbology used on that display. Regardless

of the display used, the response to the first command in a multicommand sequence took an average of 1/2 second longer than the response to subsequent commands in the sequence. There was a statistically significant difference in the response time to commands for vertical maneuvers (climb and descend) as compared to commands for horizontal maneuvers. Response to commands was somewhat faster for vertical versus horizontal maneuvers, but the difference was only 1 second, which does not have a major impact on the system design.

- Miss Distance. Seven of the 516 conflict situations resulted in miss distances of less than 500 feet slant range (See Table S-2). An analysis of these seven incidents revealed a correlation with individual pilot performance. One pilot accounted for two of these seven incidents, and the other five pilots also exhibited below average miss distances in their other encounters. Conflict geometry was a factor in resultant miss distance. Fewer close conflicts occurred while the CRT display presentation was being used, and more conflict situations developed when the IVSI display was being used. The presence of traffic information was cited by the pilots and test observers as the reason for this difference between displays.

Table S-2. ACHIEVED MISS DISTANCE

Conflict Statistics	Display Type			Total
	IVSI	LED	CRT	
Total Number of Miss Distance Measurements	191	160	165	516
Number of Close Encounters (< ½ mile in range and < 500' in altitude)	27	28	13	68
Percentage of Close Encounters to Total Encounters	14	18	8	13

5. RECOMMENDATIONS

The pilots who participated in this test spontaneously recommended further evaluation and demonstrations that should be accomplished before the implementation of an ASA system. These recommendations cover both the development and operational implementation of the ASA program, and are primarily

directed toward flight evaluation to ensure the reliable performance of the ASA system when it becomes operational. Specific recommendations are discussed in the following subsections.

5.1 Flight Test

Consideration should be given to both operational and experimental flight tests. The ASA logic should be subjected to an operational flight test in an actual airline operational environment to achieve the following objectives:

- Determine the incidence of ASA alarms
- Determine the incidence of false ASA alarms
- Establish the sensitivity of ASA performance to aircraft density
- Identify pilot reactions to ASA commands in actual flight conditions

Experimental flight tests should be conducted by the FAA to stress the ASA logic and establish the satisfactory operation and reliability of the ASA concepts.

5.2 ASA Logic Modifications

The ASA logic should be modified to provide the same minimum display time for limit commands as provided for positive and negative commands. In addition, specific geometries, such as the "tail chase" geometry, should be investigated further to determine if the situation might be improved by procedural instructions.

5.3 ASA Displays

The design and selection of the best ASA display is dependent on the aircraft's normal operational environment. Specific consideration should be given to display location, use of color, inclusion of traffic advisories, symbolic representation of information, and combined function displays (normal instrument function plus ASA).

5.4 ATC and Flight Procedures

Before implementation of an ASA system, a set of pilot procedures should be developed in the areas of response to ASA traffic advisories, response to ASA commands, and communication with ATC during a conflict situation. A training program should be established to explain how the system functions, what each type of command advisory represents in terms of a traffic situation, and what command sequences might be produced. Normally, the development of pilot training programs and flight procedures is the responsibility of the aircraft operator, subject to the approval of

the FAA. It is expected that pilot procedures will be developed by a committee composed of airline industry personnel and approved by the Federal Aviation Administration.

GLOSSARY

ACAS	Airborne Collision Avoidance System
ALPA	Air Line Pilots Association
ASA	Aircraft Separation Assurance
ATA	Air Transport Association
ATARS	Automatic Traffic Advisory and Resolution Service
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
BADCOM	Display device developed by the Federal Aviation Administration that uses lighted indicators to display commands and relative intruder position.
BCAS	Beacon Collision Avoidance System
CAS	Collision Avoidance System
CDI	Course Deviation Indicator
CDTI	Cockpit Display of Traffic Information
CRT	Cathode Ray Tube
DABS	Discrete Address Beacon System
EHSI	Electronic Horizontal Situation Indicator
FAA	Federal Aviation Administration
FDI	Flight Director Indicator
FIM	Fillmore VOR
FL	Flight Level
FOI	Flight Operations Instructor
FPM	Feet Per Minute
F/E	Flight Engineer
F/O	First Officer
GMN	Gorman VOR
HSI	Horizontal Situation Indicator
HUD	Head-Up Display
IAS	Indicated Airspeed
IFR	Instrument Flight Rules

ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
Intruder	An aircraft which violates the PWI criteria for own aircraft and represents a potential threat.
IVSI	Instantaneous Vertical Speed Indicator
KIAS	Knots Indicated Airspeed
LAX	Los Angeles International Airport
LED	Light Emitting Diode
LMT	Limit
MSL	Mean Sea Level
NAFEC	National Aviation Facilities Experimental Center
NBAA	National Business Aircraft Association
OPR	Operator
ORD	Chicago O'Hare International Airport
PMD	Palmdale VOR
POM	Pomona VOR
PWI	Proximity Warning Indication
SAN	San Diego International Airport
SBA	Santa Barbara VOR
SFO	San Francisco International Airport
SID	Standard Instrument Departure
SLI	Seal Beach VOR
SMATC	Short Message Air Traffic Control Device
SOP	Standard Operating Procedure
STAR	Standard Terminal Arrival Route
S/O	Second Officer
Tau	A derived quantity usually expressed in seconds which represents the time to closest approach of two aircraft. Tau is defined as range divided by range rate.
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VOR	Very High Frequency Omnidirectional Range
VTU	Ventura VOR
VSI	Vertical Speed Indicator
3ATI CRT	Cathode Ray Tube device that can be installed in a standard 3 inch instrument case.

CHAPTER ONE

INTRODUCTION

1.1 PROJECT OVERVIEW

The Systems Research and Development Service of the Federal Aviation Administration (FAA) is conducting a program to develop an Aircraft Separation Assurance (ASA) system for use within the National Airspace System (NAS). The program includes examination of methods for detecting potential aircraft conflicts, resolving such conflicts, and displaying appropriate information to pilots and controllers. Work is progressing in all areas. This report provides the results of an airline cockpit simulator study that was designed to determine the cockpit information requirements for an airborne collision avoidance system.

The study involved the simulation of a jet transport aircraft equipped with an Aircraft Separation Assurance System operating in the near-term traffic environment projected for a major air transportation hub. The overall objective of the study was to determine the cockpit information requirements for an airborne collision avoidance system within a realistic airline operational environment. Specific objectives are presented in Section 1.2.

Previous simulations of ASA systems have concentrated on light aircraft operated by one pilot in a one-on-one encounter (see NAFEC technical letter report NA-77-73-LR). This ASA simulation was unique in that it used a jet transport cockpit simulator operated by qualified flight crews in a realistic traffic environment.

The selected ASA display devices covered a range of techniques and capabilities. One device, the modified Instantaneous Vertical Speed Indicator (IVSI), combines the ASA function with an existing instrument. The other displays represent new technology or a new application of existing technology to a cockpit display.

The selected ASA collision avoidance concept used in the simulation was the Beacon Collision Avoidance System (BCAS) developed by the Federal Aviation Administration*. The collision avoidance logic** operates in two

FAA BCAS Concept, Report No. FAA-EM-78-5, April 1978.
***Initial Collision Avoidance Algorithms for the Beacon-Based Collision Avoidance System*, Report No. FAA-RD-77-163 (as revised), April 1977.

modes. The first mode, which is analogous to the logic used in the active BCAS concept, operates on range and altitude information from other aircraft. This mode is referred to in this report as *active mode ASA*. The second mode, which is analogous to the logic used by the full BCAS concept, uses bearing information in addition to range and altitude and is referred to as *full mode ASA*.

ARINC Research Corporation conducted this airline simulation effort with one subcontractor, United Airlines. United Airlines provided a flight simulator, test crews, and maintenance support for the simulation. The work, which began 9 December 1977, was performed under Contract DOT-FA78-4091. The overall contract effort is structured into Part I, Simulation; and Part II, Preparation for Operational Testing. This report describes Part I. A separate report* describes Part II and provides a preliminary plan for the operational flight test of the Active Beacon Collision Avoidance System (BCAS).

The following seven tasks constitute the Part I contractual effort:

1. ASA Simulation Verification. Working jointly with the Air Transport Association (DABS/ATARS/BCAS Task Force) and FAA, ARINC Research Corporation developed conflict geometries and scenarios that represented realistic traffic situations and exercised the collision avoidance algorithms to the full extent.

2. Prepare ASA Simulator Evaluation Test Plan. A Test Plan** was developed to define the specific test conditions and the number and type of experiments performed.

3. Develop ASA Simulation Control Computer. A minicomputer system was procured and programmed to provide an ATC environment for the simulation test bed. The minicomputer was also used to provide the interface with the airline simulator, control the ASA devices, and collect and record test data.

4. Install ASA Simulation Control Computer in Simulation Test Bed. The hardware and software interface requirements were defined, and the ASA systems simulator was integrated into the test bed.

5. Conduct ASA Concept Evaluation. Various ASA concepts developed by the DABS/ATARS/BCAS Task Force and FAA were evaluated, with airline pilots being utilized as subjects, to determine the impact of these concepts in the cockpit environment.

6. Analyze Data and Prepare Report. Data were collected and analyzed. The results of that analysis appear in this report.

**Preliminary Plan for the Operational Flight Test of the Active Beacon Collision Avoidance System*, ARINC Research Publication 1343-01-2-1936, June 1979.

***Experimental Test Plan for the Evaluation of Aircraft Separation Assurance System Using Airline Flight Simulators*, ARINC Research Publication 1343-01-1-1753, November 1978.

7. Document the Simulation Configuration. A description of the features and capabilities of the experimental test bed was developed. It is included in this report.

1.2 OBJECTIVES

The primary objective of the experiment was to determine the cockpit information requirements for an airborne collision avoidance system. A significant secondary objective was to evaluate the operational impact of the introduction of Aircraft Separation Assurance Systems in commercial air carrier aircraft. A further objective was to expose a number of air carrier pilots to the ASA concept by their participation in the experiment and to obtain their opinions regarding the ASA displays, the expected escape maneuvers, and the ASA concept as currently defined.

The candidate ASA display devices selected for use in the simulation included three distinct display types: (1) an existing electromechanical device (IVSI) modified to display ASA commands using lighted display segments, (2) an alphanumeric device that could display a 40-character message (using LED technology) to provide both ASA commands and traffic advisories, and (3) a CRT device that combines alphanumerics and symbols to provide a graphical presentation of the conflict situation and an alphanumeric readout of the ASA command. These candidate displays represented selections from a larger field of candidates that had been progressively narrowed and redefined as a result of previous related experiments; they were selected in coordination with representatives of the Air Transport Association, the Air Line Pilots Association, and the FAA.

Although airline pilots' opinion have been obtained previously on a volunteer basis, this is the first time a relatively large number of professional line-qualified crews have evaluated these devices in standard-configuration air-carrier simulators. Their opinions and suggestions relating to operational procedures are considered invaluable.

1.3 REPORT ORGANIZATION

This report is organized into six chapters and seven appendixes. Chapter Two describes the experimental approach used in conducting the evaluation. Chapter Three is a discussion of the experimental design and its content. Chapters Four and Five present analyses of the qualitative and quantitative data collected, respectively. Chapter Six includes conclusions drawn from the analysis and recommendations for additional testing and system implementation.

The following appendixes are included in Volume II of this report:

Appendix A - Flight Scenarios

Appendix B - Subject Pilot Advance Briefing

Appendix C - Subject Pilot Pre-Briefing

Appendix D - Flight Crew Questionnaire

Appendix E - Supplemental Flight Crew Questionnaire

Appendix F - Data Analysis Formulas

Appendix G - Test Bed Description Details

CHAPTER TWO

EXPERIMENTAL APPROACH

In this chapter, the overall evaluation approach is discussed and the experimental equipment is described. The discussion is intended to provide a functional overview of the simulation test bed. Specific details on the test bed design (e.g., interface techniques, software design) are included in Appendix G.

2.1 OVERALL APPROACH

The experimental test plan describes a program of evaluation using professional flight crews in a United Airlines Boeing 727 cockpit simulator. Six different missions or scenarios of about 45 minutes each, representing typical airline flights, were conducted to evaluate the ASA concepts. Each flight crew flew three of the six scenarios and was exposed to each of the three ASA displays. Twenty-eight crews (consisting of volunteers recommended by the Air Line Pilots Association, airline management, government, and industry) participated in the program. Two- or three-subject crews were used, for a total of 74 participants. Clearances were provided by a local air traffic controller, who also "provided control" for other aircraft in the scenario to create a realistic communications workload. The simulator was equipped with a computer-generated visual system that projected a night visual scene on the windshield of the cockpit. This system was modified so that other simulated aircraft would appear within the scene when their position relative to the simulator cockpit was within the forward windshield area.

Both qualitative and quantitative data were collected from the simulation. Qualitative data were developed from questionnaires and comments made by crew members and test observers. Quantitative data were collected by a minicomputer system, which stored data on simulator position, velocity, and attitudes; ASA display status; and unique simulation events.

The data collected were grouped and analyzed with respect to influencing or suspected influencing factors. Appropriate statistical tests were applied to the results of this analysis to identify real differences.

On the basis of this evaluation, display information items and characteristics have been ranked qualitatively and quantitatively, the impact of

introducing ASA into the National Airspace System has been discussed, and additional testing has been recommended.

2.2 SIMULATION TEST BED

Figure 2-1 is an artist's conception of the simulation test bed setup. This section describes the test bed -- an interactive, distributed processing system that includes a simulator cockpit and its associated control computer; a computer-generated image display system; a simulation control computer; a control/monitor station; and associated communications, input/output devices, and data storage devices. Omitted from this discussion are the simulation cockpit displays, which are described in Section 2.3.

The test bed was designed to permit evaluation of flight crew reactions to aircraft conflict and near-conflict situations that could present a significant element of danger if conducted in actual aircraft. The use of a simulator makes experimental problem control and data collection much simpler than would be possible in an experiment using actual aircraft. In addition, simulation presents significant cost and time advantages over an experiment that might require several transport aircraft operating in controlled airspace under the precise conditions necessary for experimental work.

2.2.1 Aircraft Simulator

The aircraft simulator selected for this experiment represents the Boeing 727 aircraft, one of the most widely used commercial jet transports. The B-727 is expected to remain in the fleets of most major airlines for the next 20 years; therefore, its performance and handling characteristics make it most appropriate for use in evaluating ASA displays.

The simulator is located in the United Airlines Flight Training Center at Stapleton International Airport, Denver, Colorado. Its cockpit replicates a B-727 aircraft in the United Airlines fleet. The cockpit module layout is shown in Figure 2-2.

Figures 2-3 and 2-4 show the captain's and second officer's instrument panels, respectively. Figure 2-5 presents a detail of the center console forward of the throttle quadrant and aft of the instrument panel. The ASA display locations are included in the diagrams for reference.

The cockpit module is mounted on a 3-degrees-of-freedom motion base that simulates the movement of an aircraft cockpit. The motion base and the aircraft instruments are controlled by a GP-4 computer, which is supplied as part of the Singer-Link-developed simulator and is located in a room adjacent to the cockpit module. Simulator control is effected through a control panel located inside the cockpit module at the second officer's station. This panel is operated by the flight operations instructor (FOI), who also served as the second officer during regular training.

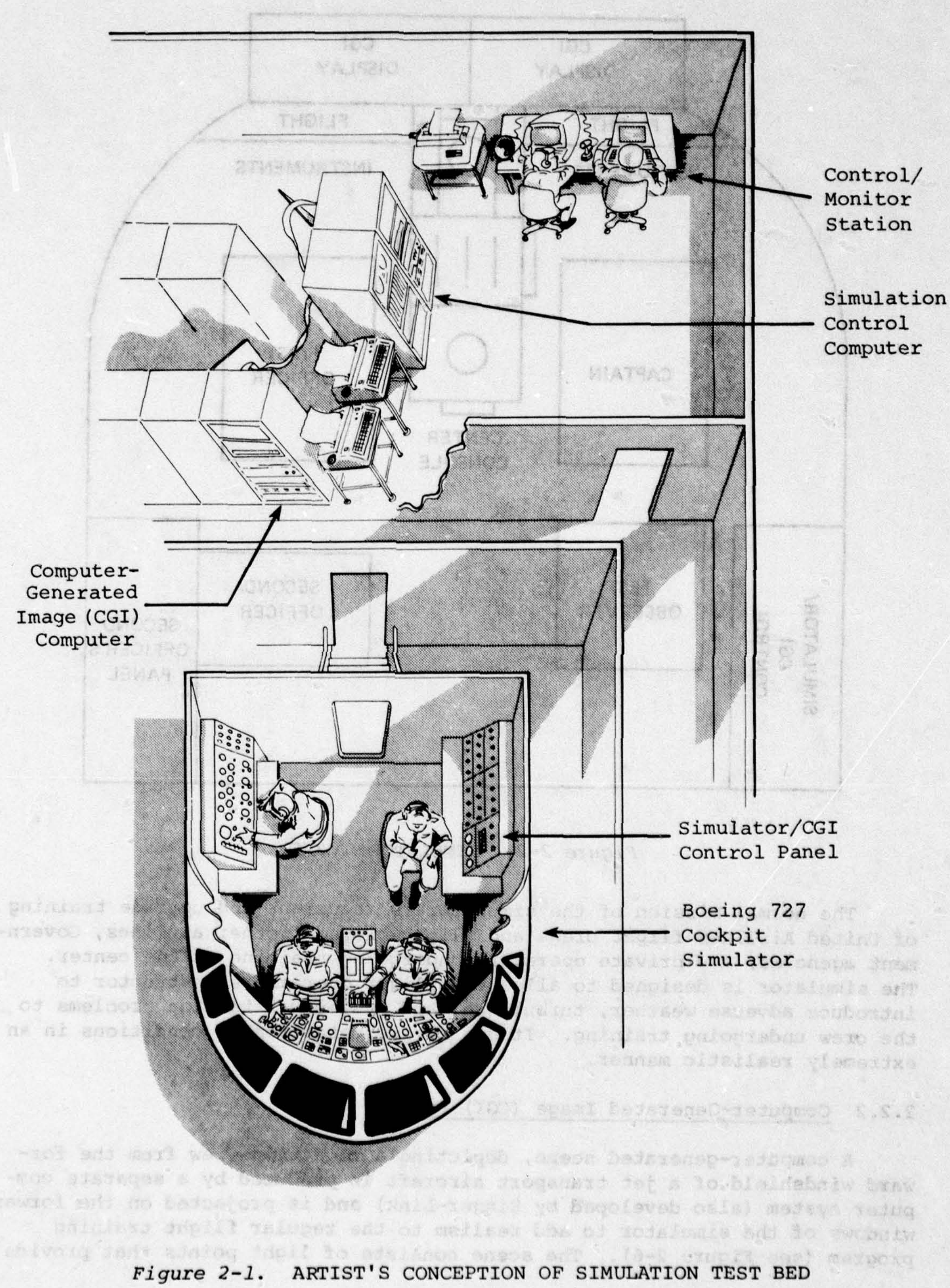

Figure 2-1. ARTIST'S CONCEPTION OF SIMULATION TEST BED

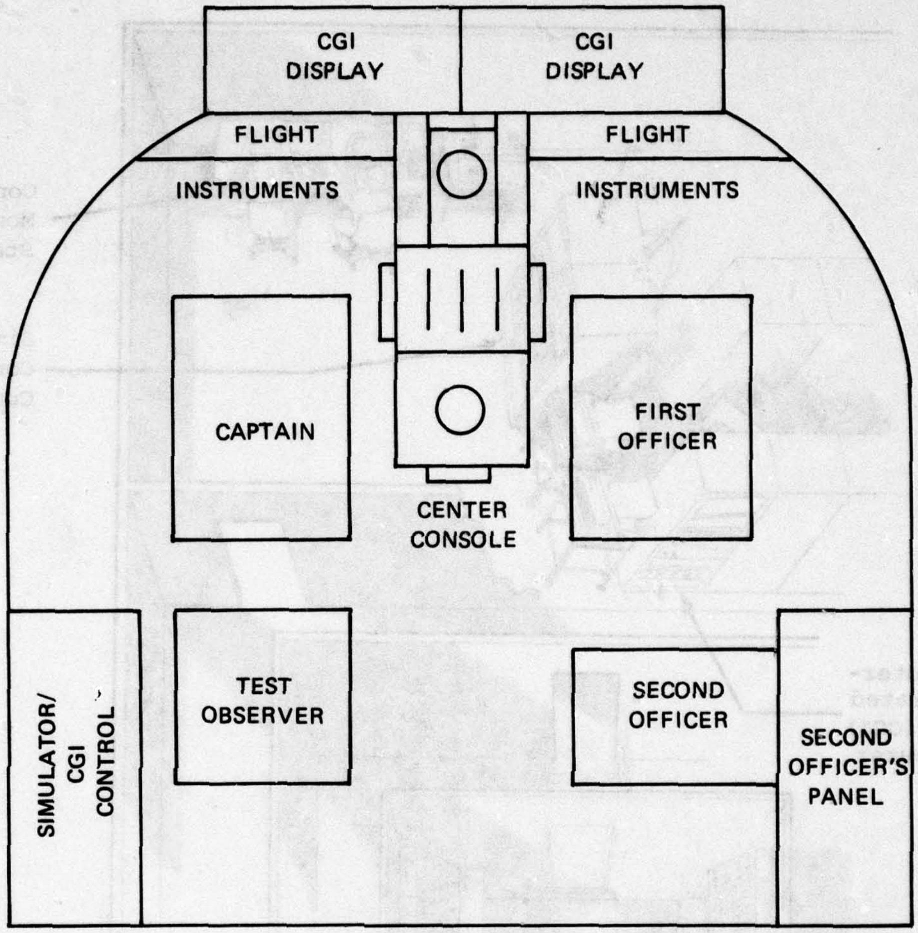

Figure 2-2. SIMULATOR LAYOUT

The normal mission of the simulator is recurrent and upgrade training of United Airlines flight crews and flight crews of other airlines, Government agencies, and private operators undergoing training at the center. The simulator is designed to allow the flight operations instructor to introduce adverse weather, turbulence, and system-malfunction problems to the crew undergoing training. It can create catastrophic conditions in an extremely realistic manner.

2.2.2 Computer-Generated Image (CGI) System

A computer-generated scene, depicting a nighttime view from the forward windshield of a jet transport aircraft is produced by a separate computer system (also developed by Singer-Link) and is projected on the forward windows of the simulator to add realism to the regular flight training program (see Figure 2-6). The scene consists of light points that provide

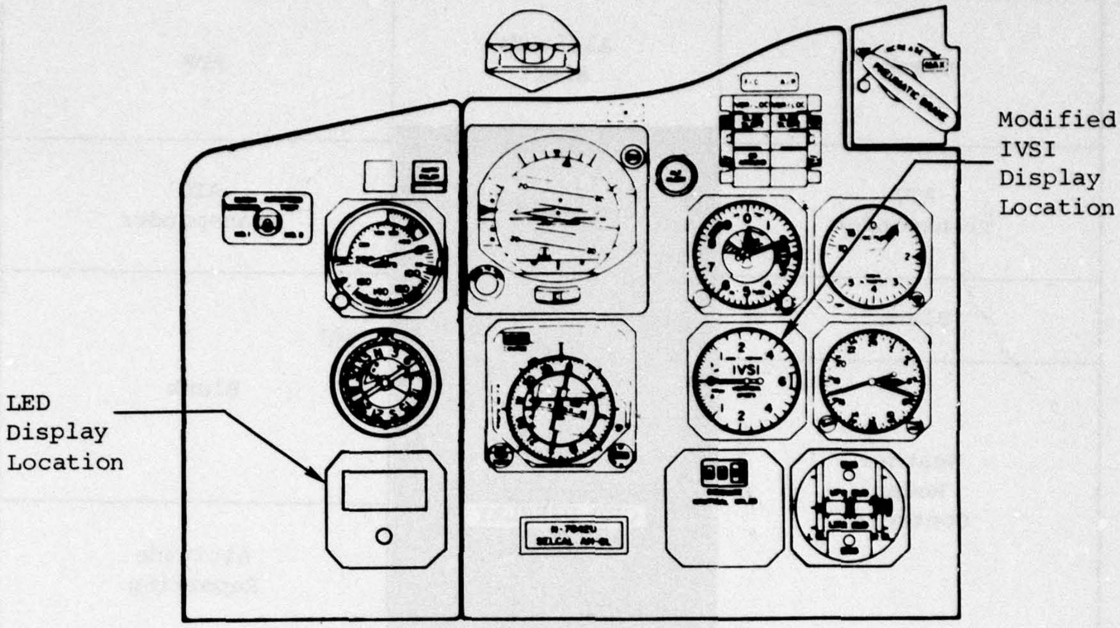

Figure 2-3. CAPTAIN'S PANEL

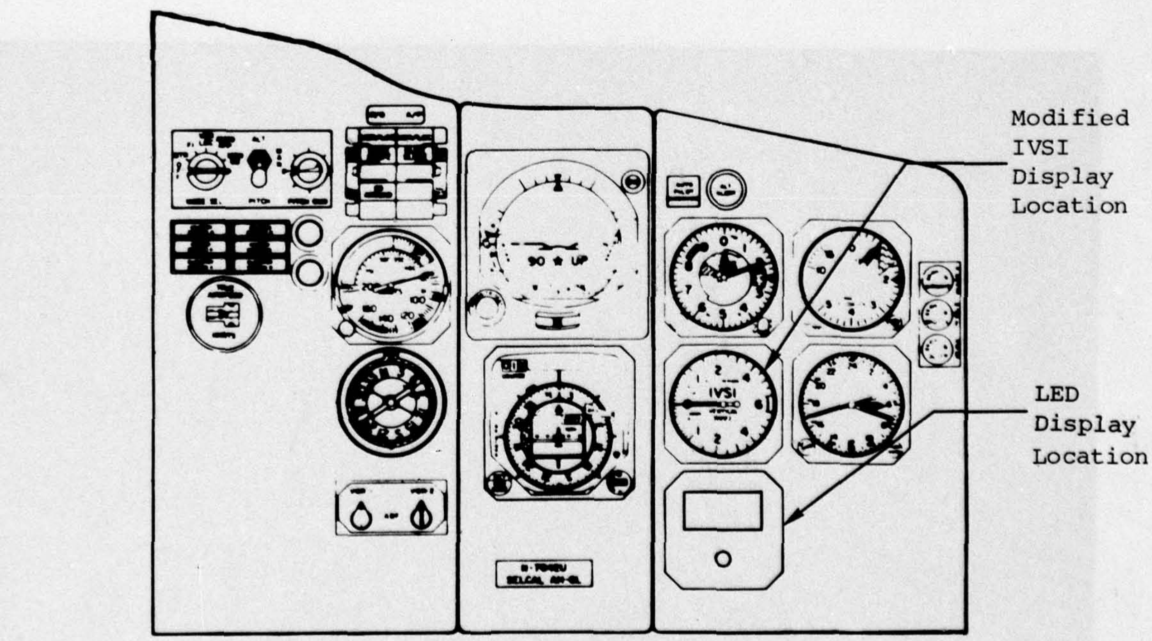

Figure 2-4. FIRST OFFICER'S PANEL

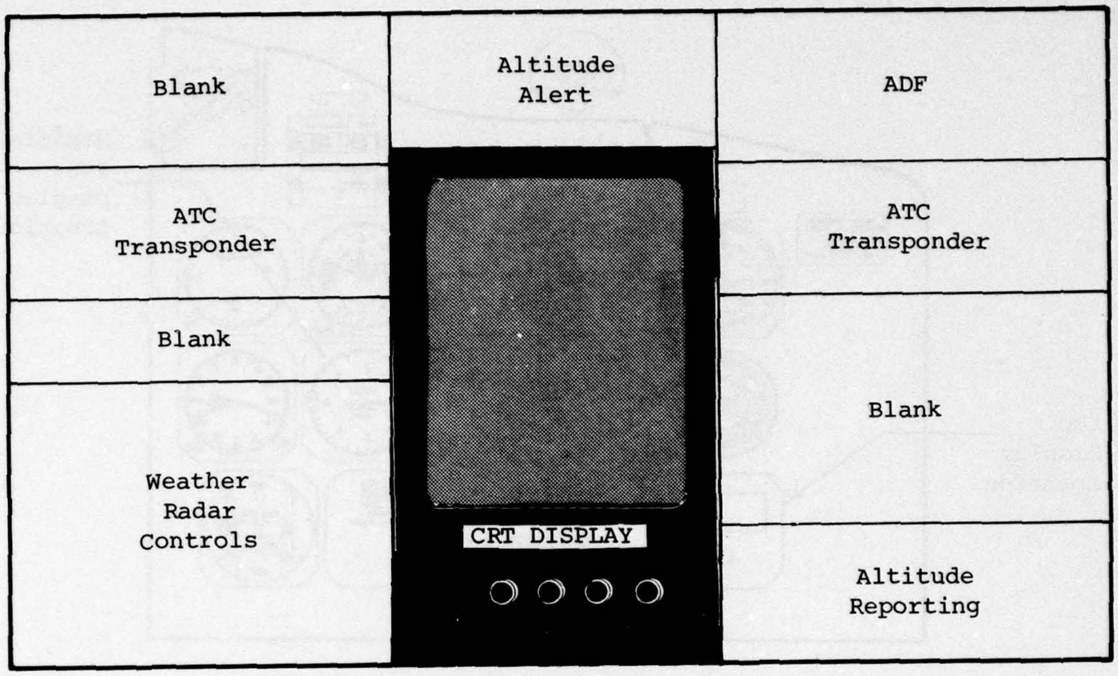

Figure 2-5. B-727 FORWARD PEDESTAL

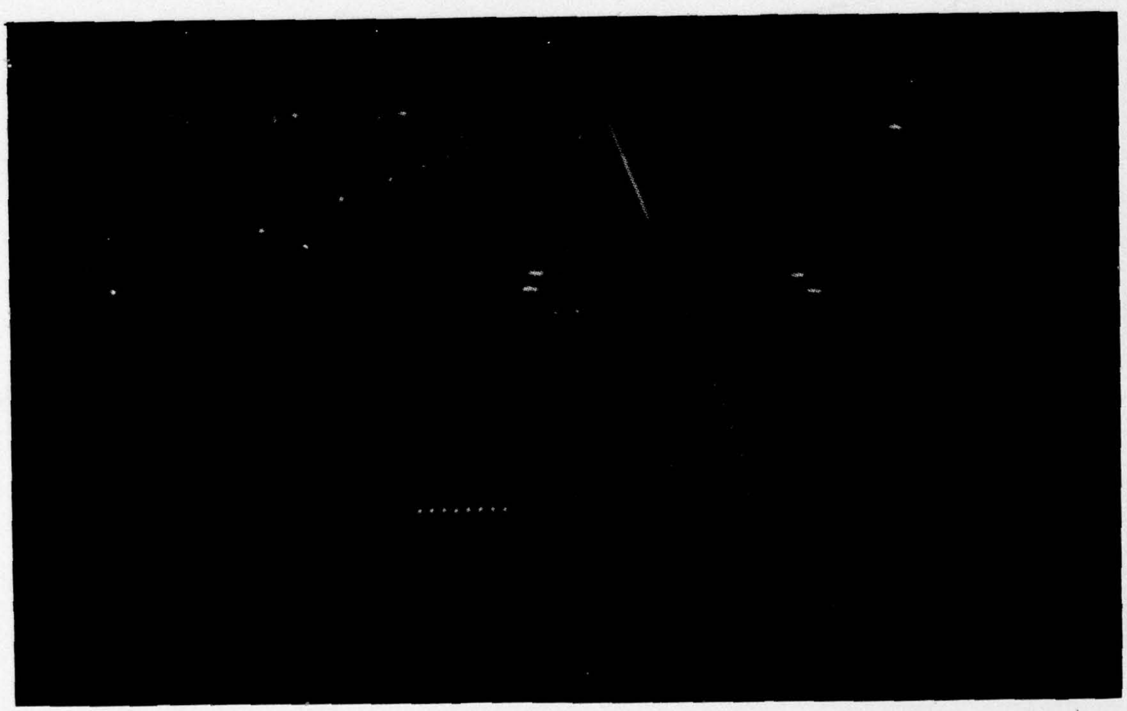

Figure 2-6. COMPUTER-GENERATED NIGHT VISUAL SCENE

a full-color representation of a night landscape for a large metropolitan area, including that city's major airport.

The landscape scene, consisting of more than 7,000 lights, is created from a data base of 15,000 lights. This data base is stored in the CGI computer as a file of 3-dimensional coordinates characterized as to color and intensity. Simulator position and attitude are obtained through an interface to the GP-4 computer. The displayed lights are those which fall into the forward field of view, which is approximately 45° right, 55° left, 30° up, and 60° down. Additional controls are available on the simulator CGI control panel (Figure 2-2) to simulate various visibilities, ceiling heights, cloud tops, and ground fog.

For purposes of this experiment, the programming of the CGI computer was modified so that other aircraft could be simulated in the visual scene. Each aircraft was represented by a pair of lights consisting of a flashing red and a flashing white light that were spaced 60 feet apart. Those simulated aircraft, whose relative position to the simulator fell within the forward viewing area, were displayed within the visual scene. Data for the other aircraft were obtained through an interface to the simulation control computer (Subsection 2.2.3). The position information was updated 20 times per second to provide display continuity. The red and white lights were processed independently to provide proper viewing perspective. In all other respects, the moving lights representing the other aircraft were controlled in the same manner as the fixed ground lights.

2.2.3 Simulation Control Computer

The simulation control computer produced the ATC environment for the simulation test bed and was used to control simulation activities. The ATC environment software consisted of the following features:

- Traffic and intruder generation logic
- Simulator cockpit interface
- Alpha/beta tracker
- Detection and resolution logic
- Cockpit display logic
- ATC displays

The simulation control features included simulation initialization, simulation interaction logic, and data recording algorithms.

The simulation control computer was a Government-provided Digital Equipment Corporation PDP-11/34 minicomputer. The minicomputer was interfaced directly to the United Airlines CGI computer by using a Digital Equipment Corporation UNIBUS window. The UNIBUS window provides an interprocessor link between computers through a common UNIBUS. Direct memory access into the "other" computer's memory is efficiently performed by using "cycle stealing" techniques.

The interface techniques used and the software design are described in Appendix G.

2.2.4 Control/Monitor Station

The control/monitor station (Figure 2-7) served two functions: simulation control and monitoring, and ATC. These functions were provided by two *input/output* devices interfaced directly to the simulation control computer. A video terminal was used by the simulation controller (Subsection 3.5.2) to display information of transitory interest and to interact with the simulation. A storage tube graphic display terminal was used by the air traffic controller (Subsection 3.5.3) to display a history of the simulator and aircraft tracks during the conduct of the simulation.

2.2.5 Communications System

A private communications link (sound-powered headsets) connected the simulation controller with the test observer. The ATC controller had direct access to the simulator interphone systems for the purpose of issuing ATC instructions. Examples of the types of communications are discussed in Chapter Three.

Figure 2-7. CONTROL/MONITOR STATION

2.2.6 Data Recording Equipment

Several different media were used to record data. Simulator parameters (position, velocity, and attitude), command and intruder data, and simulation controller inputs were recorded on high-speed disks and later transferred to magnetic tape for more permanent storage. Pilot opinion was recorded on questionnaires. Cassette tape recorders were used to record cockpit chatter, selected observer comments, and discussion during a debriefing session.

2.3 SIMULATION COCKPIT DISPLAYS

The test displays selected for use in the simulation represent three distinct methods for presenting ASA information to the flight crew. Each method corresponds to a different display technique and a different level of ASA information. The selected test displays are as follows:

- Modified Instantaneous Vertical Speed Indicator (IVSI)
- Light Emitting Diode (LED) Display
- Cathode Ray Tube (CRT) Display

The modified IVSI uses lighted indicators to display ASA commands. The LED display presents ASA commands and traffic advisories in alphanumeric form using LED technology. The CRT display provides a graphical presentation of ASA commands and traffic advisories. An audio alert, common to all displays, is sounded whenever a new ASA command is displayed.

All of the selected displays can be used with either an active or full mode ASA system or a combination system. In the simulation test bed, the displays were driven by the simulation control computer, which tracked the position of the simulator and all scenario aircraft, applied the ASA detection and resolution logic, determined the appropriate advisory or warning message, formatted the message for the display under test, and transmitted the message to the cockpit display.

The ASA logic operates in the following conceptual manner. The logic defines a protected volume of airspace around each aircraft and compares aircraft positions to determine if that airspace has been violated. The criteria for establishing the protected volumes include range, range rate, and tau (range divided by range rate) in both the horizontal and vertical planes. Two volumes are established. A larger volume is used for determining potential threatening aircraft. This logic is often called pilot warning indication (PWI) logic and causes the display of traffic advisory information. Violating the smaller protected volume requires action by the aircraft involved and causes the display of ASA commands.

The displays used represent a good engineering design; however, optimization of the displays was outside the scope of this simulation. Comments received from the test crews have provided some insight into features that should be included in any optimized display.

The display methods used were selected from a larger set (Table 2-1) in coordination with pilot, airline, and Government committees. Seven types of displays were presented. The recommended selection criteria were as follows:

- Each display should contain a different level of information content.
- Each display should represent a different technological approach.
- All displays should be operated by the same ASA logic.

An additional factor considered was the installation of the displays into the cockpit simulator. The simulator could not be dedicated to the program on a full-time basis and had to be returned to its certified configuration after each test session. In addition, major modifications could not be made to the instrument panels. Therefore, the selected displays would have to replace existing instruments and meet their size specifications. This was not a serious limitation, since similar consideration will be necessary for actual implementation.

Table 2-1. ASA DISPLAY FUNCTIONAL ASSESSMENT

Displays	Vertical Commands	Horizontal Commands	Traffic Situation	Proximity Warning Indication (PWI)	Limit Vertical	Limit Horizontal
IVSI	Yes	Requires Modification	No	Perhaps with Modification	Yes	Yes
SMATC	Yes	Yes	No	Limited	Yes	Yes
BADCOM	Yes	Yes	No	Yes	Yes	Yes
CDTI Symbology Only	No	Yes	Yes	Yes	No	Yes
CRT Alphanumeric and Symbology	Yes	Yes	No	Limited Yes	Yes	Yes
3ATI CRT	Yes	Yes	No	Limited Yes	Yes	Yes
LED Alphanumeric and Symbology	Yes	Yes	No	Yes	Yes	Yes

2.3.1 Modified Instantaneous Vertical Speed Indicator (IVSI)

The modified IVSI display is the only test display that combines the ASA function with another display function. The test display replaced the existing IVSI on both the captain's and first officer's instrument panels (Figures 2-3 and 2-4). Vertical speed on the test display is indicated in the same manner as on the standard IVSI.

Modification of the standard IVSI to allow presentation of ASA commands consisted of the following additions (see Figure 2-8 for an artist's rendition of the display):

- Lighted red arrows for all positive commands
- Lighted yellow indicators for negative horizontal commands
- Lighted yellow arc segments for limit vertical commands

The positive command arrows instruct the pilot to climb, descend, turn right, or turn left; they are labeled "climb", "dive", "right", and "left", respectively. (See Figure 2-9A for a photograph of the IVSI illustrating a descend command.) The negative horizontal command indicators instruct the pilot to stop turning right or left and are labeled "no right" and "no left." The limit vertical command lighted arc segments are unlabeled and instruct the pilot to limit his climb or descent to 500, 1,000, or 2,000 feet per minute (FPM) (see Figure 2-9b for a photograph

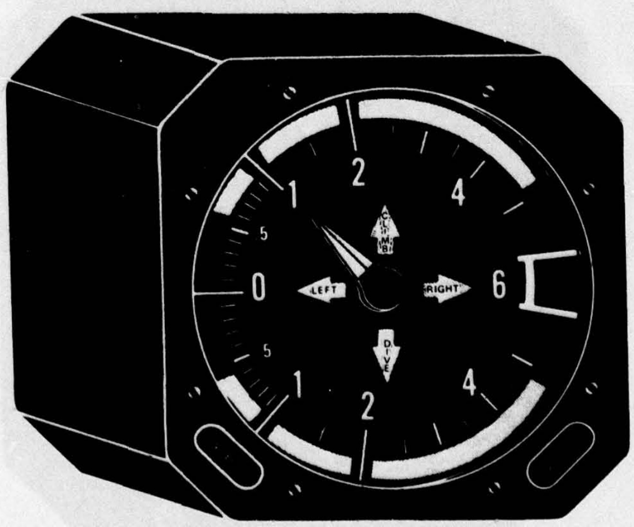

Figure 2-8. ARTIST'S DRAWING OF MODIFIED IVSI

Figure 2-9a. IVSI ILLUSTRATING DESCENT COMMAND

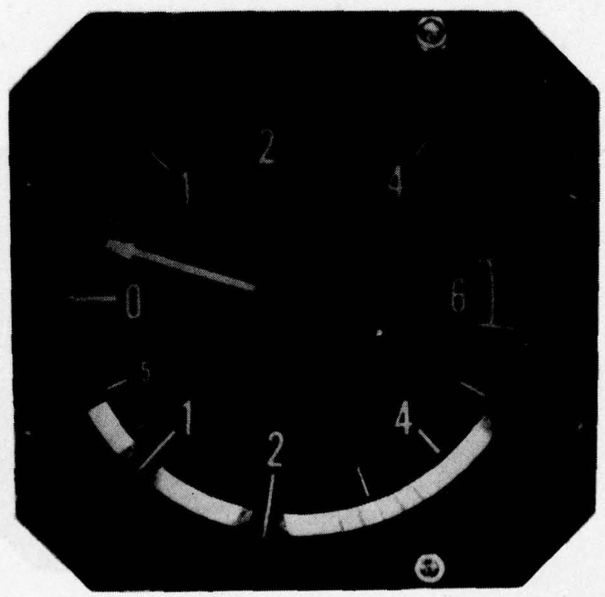

Figure 2-9b. IVSI ILLUSTRATING LIMIT DESCENT COMMAND

of the IVSI illustrating a limit-descent command to 500 FPM. The lighted arc segments are used in combination to produce the desired command. A single segment between the 2,000 FPM and 6,000 FPM positions on the IVSI is lighted to indicate a limit-climb command or limit-descent command of 2,000 FPM. Two segments, one between the 1,000 FPM and 2,000 FPM positions and one between the 2,000 FPM and 6,000 FPM positions, are lighted to indicate a limit climb or descent to 1,000 FPM. The lighting of all three segments indicates a command to limit climb or descent to 500 FPM. To reduce confusion, pilots were instructed simply to keep the vertical speed indicator out of the lighted arc segments.

Only one command can be displayed at any time, and the display remains lighted for the duration of the command. At the end of the command, the display is cleared.

2.3.2 LED Display

The LED display used in the ASA simulation represents the first application of this technology in an air transport aircraft cockpit. The device is a three-color display that provides traffic advisory messages and ASA commands in alphanumeric characters, augmented by a limited number of symbols. The traffic advisory messages are presented in a shorthand notation similar to that which is used by many pilots. Two LED displays were installed, one on the captain's instrument panel and one on the first officer's instrument panel (see Figures 2-3 and 2-4).

The LED display (see Figure 2-10) is capable of producing up to 40 characters or symbols arranged in 4 lines of 10 characters each. However, because of parallax problems caused by display position, only the 3 lower lines were usable. Each line of text is color-coded according to the type of message that is being displayed. Traffic advisories are displayed in green, negative and limit vertical commands in amber, and positive commands in red.

The traffic advisories are abbreviated into a 10-character message consisting of intruder bearing, range, heading, and altitude*. The bearing is represented by a clock position (1 to 12) followed by a degree (°) indication. Range is displayed as a two-character, left-justified expression in nautical miles. The intruder heading is truncated into one of the eight cardinal directions and displayed as a two-character expression. Altitude is expressed in hundreds of feet Mean Sea Level (MSL) in a three-character field. For example, Figure 2-10 indicates traffic at 12 o'clock, 2 miles away, southeastbound, at 6,100 feet MSL. In the experiment, advisories were presented when an aircraft violated the ASA PWI criteria.

Up to three traffic advisories can be displayed concurrently in non-conflict situations (i.e., the traffic situation is such that an ASA command is not required). Advisories are displayed on lines 2, 3, and 4 starting with the bottom line. The list is scrolled down when an advisory disappears.

*In Active Mode, bearing and heading were not displayed.

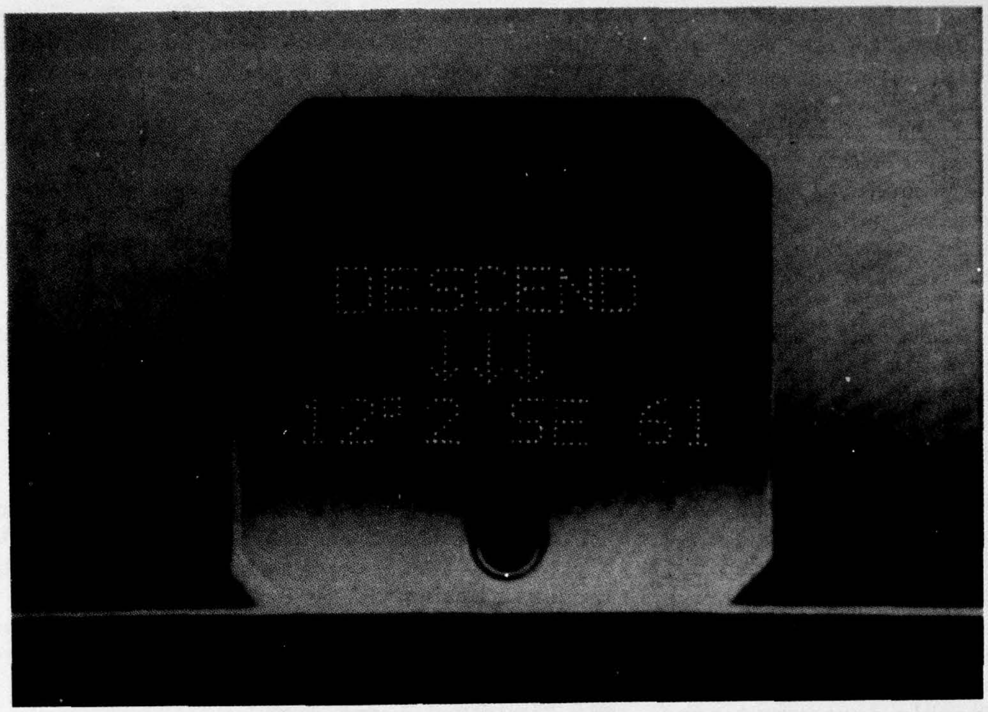

Figure 2-10. LED DISPLAY

When an ASA command is required, a single traffic advisory (for the aircraft involved in the conflict) is presented on line 4, with the command displayed on lines 2 and 3. The command formats appear in Table 2-2.

Only one command can be displayed at any time, and the display remains lighted for the duration of the command. When the command is deleted, the display is again capable of showing as many as three traffic advisories. If there are no required traffic advisories, the display is cleared.

The LED display was developed by the Aero Products Division of Litton Systems, Inc., who provided it for use in this project. Their interest, advice, and assistance have been greatly appreciated.

2.3.3 CRT Display

The CRT display combines symbology and alphanumerics to create a graphical presentation of the conflict situation. The display was installed in the forward pedestal area of the simulator in place of the weather radar, which is not used in normal simulator training (Figure 2-5). The display is heading-oriented and own-aircraft-centered to present the same view as that which the pilot sees out of the cockpit window. The full mode presentation of the display is illustrated in Figure 2-11.

Table 2-2. PRESENTATION OF COMMANDS ON LED DISPLAY		
Command	Presentation	Color
CLIMB	↑↑↑ CLIMB	RED
DESCEND	DESCEND ↓↓↓	RED
TURN RIGHT	⟶ RIGHT ⟶	RED
TURN LEFT	⟵ ⟵ LEFT	RED
DON'T CLIMB	DON'T CLIMB	AMBER
DON'T DESCENT	DON'T DESCEND	AMBER
DON'T TURN RIGHT	DON'T TURN RIGHT	AMBER
DON'T TURN LEFT	DON'T TURN LEFT	AMBER
LIMIT CLIMB 500 FPM	LMT 500 CLIMB	AMBER
LIMIT CLIMB 1000 FPM	LMT 1000 CLIMB	AMBER
LIMIT CLIMB 2000 FPM	LMT 2000 CLIMB	AMBER
LIMIT DESCENT 500 FPM	LMT 500 DESCENT	AMBER
LIMIT DESCENT 1000 FPM	LMT 1000 DESCENT	AMBER
LIMIT DESCENT 2000 FPM	LMT 2000 DESCENT	AMBER

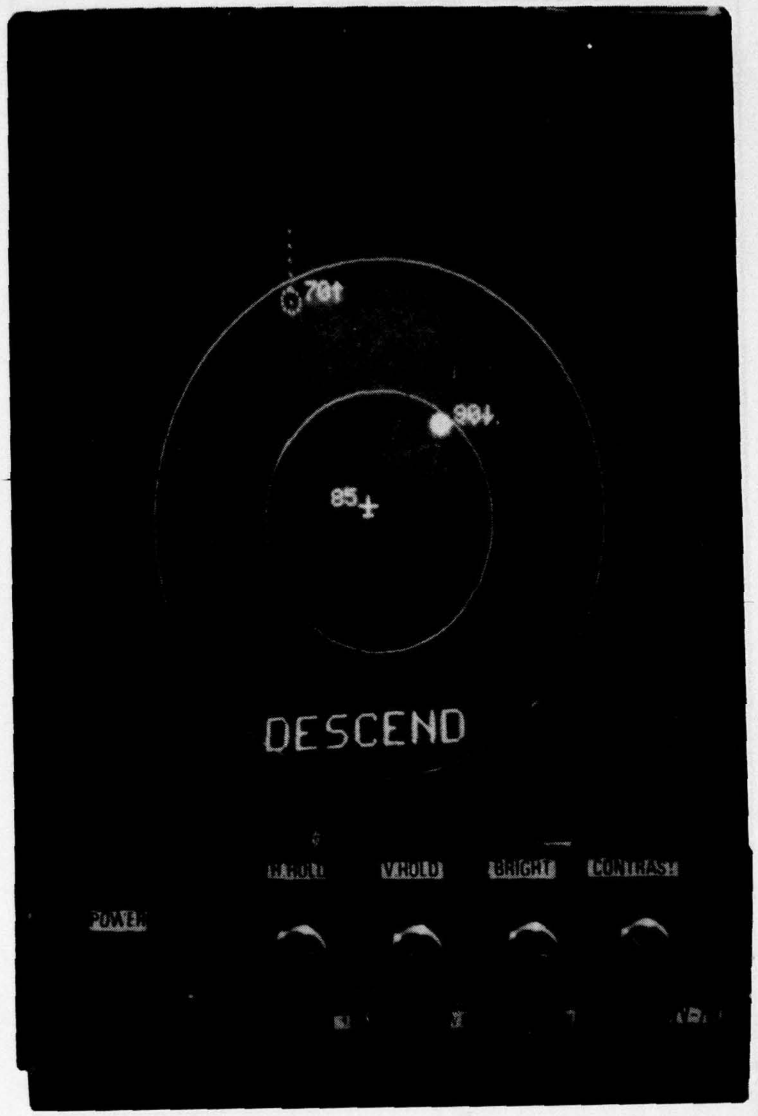

Figure 2-11. CRT DISPLAY - FULL MODE

Own-aircraft is symbolized by a small aircraft symbol positioned in the center horizontally and positioned two-thirds down from the top vertically. A numerical data block positioned to the left of the symbol provides own-aircraft altitude in hundreds of feet MSL. The aircraft symbol is surrounded by range rings that correspond to ranges of 3 and 6 miles.

Aircraft that violate the ASA PWI logic and are within the range limitations of the display (6 miles on either side or behind, 9 miles ahead) are symbolized by a ring of dots. Present and previous aircraft position is represented by a trail of dots that begins at the center of the aircraft symbol. The trail or history corresponds to the actual position in space that the aircraft occupied relative to own-aircraft present position. To the right of the aircraft symbol is a numerical data block containing the aircraft's altitude in hundreds of feet and altitude trend. This trend is represented by an arrow for climbing or descending aircraft; when the aircraft is level, there is no symbol.

Intruder aircraft (i.e., those aircraft which violate the ASA detection logic and cause an ASA command to appear) are displayed in the same manner as other aircraft with the exception that the aircraft symbol is filled in.

ASA commands are displayed in large alphanumerics at the bottom of the screen. The commands are formatted on a single line by using the same terminology and abbreviations used on the LED (Table 2-2). Arrows are not part of the positive command presentation, however.

If there are no required traffic advisories or commands, the display consists of the own-aircraft symbol and associated data block and the two aircraft range rings.

In active mode, since only range and altitude information is available, an entirely different display presentation is required (see Figure 2-12). An alphanumeric presentation was used; it consisted of a heading declaring the ASA mode of operation and specifying that displayed data will consist of range and altitude of an intruder aircraft. Traffic advisories are presented for intruder aircraft only. Range is displayed in nautical miles and altitude is in hundreds of feet MSL. Commands are presented in the same manner as previously described. The rings on the display were not used during active mode but were present because they were painted on the display face; however, because of the low ambient light level in the cockpit simulator, they were less prominent than they appear in the photographs.

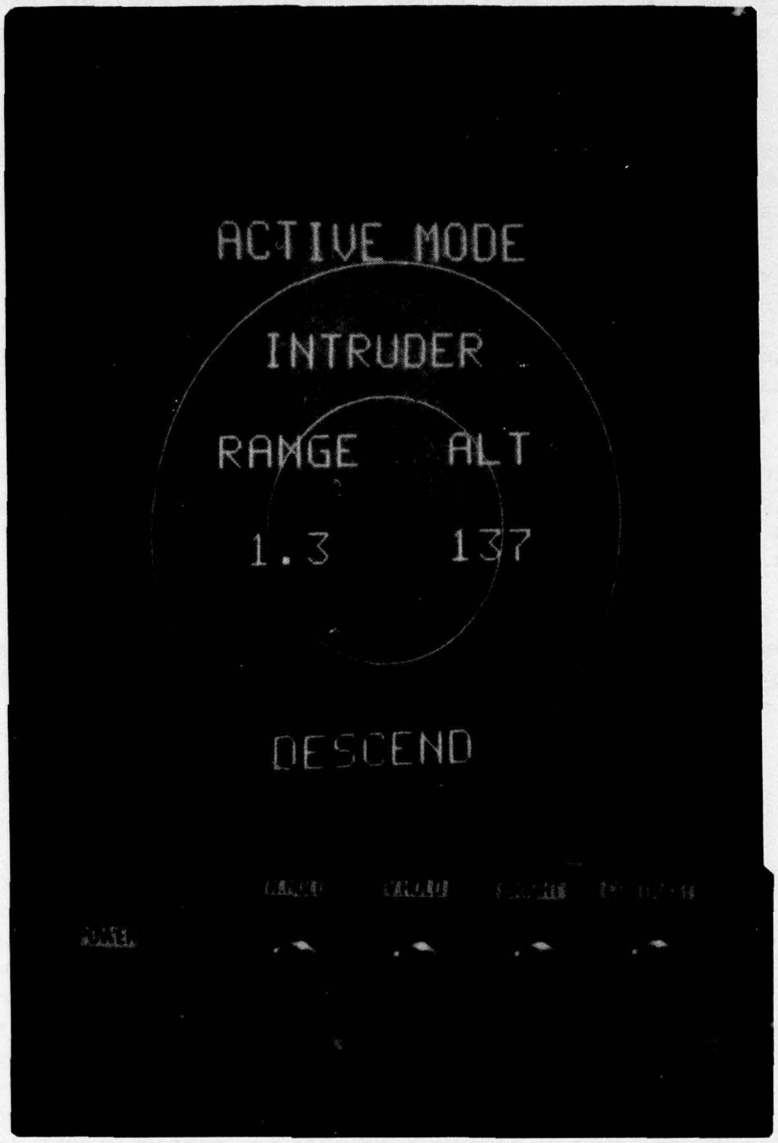

Figure 2-12. CRT DISPLAY - ACTIVE MODE

CHAPTER THREE

DESIGN AND CONDUCT OF EXPERIMENT

The overall evaluation objectives are expanded into specific objectives in this section. The development of an experimental test was based on these specific objectives and required measurements of the effects of various factors on pilot performance in a conflict situation. The procedure used to acquire experimental pilots and the characteristics of these pilots are discussed, and the experimental procedure is described.

3.1 SPECIFIC EVALUATION OBJECTIVES

The overall evaluation objectives stated in Chapter One were further defined in terms of specific objectives:

- To rank and determine the criticality of specific information elements that could be part of a collision avoidance display.
- To determine pilot reactions to three different techniques of displaying collision avoidance information in a cockpit using a wide range of commercial airline pilots and to rank the three display techniques on the basis of both quantitative and qualitative data.
- To determine the impact of an Aircraft Separation Assurance System on ATC and flight procedures
- To evaluate the effectiveness of ASA commands for collision avoidance.
- To measure and record the response characteristics of the subject pilots to collision avoidance commands
- To investigate the possible effects of scenario, display, and experience on pilot opinion

To meet these objectives, both quantitative and qualitative data were collected. The quantitative data were collected by data collection algorithms in the simulation control computer. Response characteristics (response time and magnitude of response), generated commands, and simulator position, velocity, and attitude were the quantifiable variables. The qualitative data were collected from the debriefing questionnaire, observations of the test observer, and the supplemental questionnaire.

3.2 EXPERIMENTAL DESIGN

The major constraint on the experimental design was availability of simulator time. Only 60 hours of simulator time was available for the experiment. A two-hour session was required to provide sufficient time for each crew to fly a scenario that included all phases of flight with each of the three displays. An analysis of sample size and sample error showed that 30 crews would provide a 95 percent confidence level in the results of the experiment.

During each 2-hour simulator session, each crew flew three scenarios, using a different ASA display for each scenario. The scenarios were selected from a pool of six scenarios, which included three westbound and three eastbound departures and arrivals. Each scenario, as described in Appendix A, consists of a flight profile typical of a departure from the Los Angeles International Airport to an assigned cruise altitude, and a descent, approach, and landing at the same airport. Los Angeles was chosen because of its availability as a data base for the computer-generated visual scene and its wide use as the operation area against which other ASA studies have focused. However, the scenario traffic densities did not represent maximum current or projected traffic densities for the entire Los Angeles airspace.

The display/scenario combinations were assigned such that each scenario was flown with each display an equal number of times. Further, the order of presentation of the scenarios and the order in which the displays were presented were evenly distributed. The crew test assignments appear in Table 3-1.

The crews used were volunteers from many of the major airlines, government, and industry. While the original design called for two subject pilots per crew, a large response from the pilot population enabled us to use three subject pilots in more than half of the experimental sessions.

The scenarios consisted of six conflicts each, the maximum number of conflicts that could reasonably be fitted into a single scenario without overloading the pilot. Each conflict represents a different conflict geometry.

3.3 EXPERIMENTAL CREWS

A written request was submitted to the Air Line Pilots Association (ALPA), Air Transport Association (ATA), and National Business Aircraft Association (NBAA) for volunteers to participate in the experiment. The request suggested that pilots be thoroughly familiar with the B-727 and preferably flying the B-727 regularly in scheduled service. The 74 pilots that participated in the program are currently flying for or are on the staffs of the following organizations (the number of volunteers from the organization appears in parentheses):

American Airlines (7)

Crew	Scenario/Display Combination		
	First Flight	Second Flight	Third Flight
1	1-A	5-C	6-B
2	1-B	6-C	5-A
3	1-A	5-B	6-C
4	5-B	6-C	1-A
5	5-A	6-B	1-C
6	1-A	4-B	5-C
7	6-C	4-A	5-B
8	4-B	1-C	6-A
9	4-C	5-A	6-B
10	5-C	6-A	1-B
11	4-C	5-A	3-B
12	3-C	4-A	5-B
13	6-A	5-B	3-C
14	3-A	4-C	1-B
15	1-B	4-C	3-A
16	6-A	2-B	1-C
17	1-C	2-A	3-B
18	5-C	3-B	2-A
19	2-B	3-C	4-A
20	2-C	3-A	4-B
21	3-A	1-B	2-C
22	3-B	2-C	6-A
23	4-A	6-B	2-C
24*	2-C	3-A	4-B
25	4-B	1-C	2-A
26	5-A	2-B	3-C
27**	6-C	4-A	5-B
28	2-A	4-C	6-B
29	2-B	3-C	4-A
30	3-B	2-A	5-C

Table 3-1. CREW TEST ASSIGNMENTS

Numbers indicate scenario used (see Appendix A). Letters indicate display used: A = IVSI, B = LED, C = CRT.

*Crew unable to reach Denver because of weather.
**Crew unable to complete simulator session because of scheduling problems.

- Continental Airlines (7)
- Federal Aviation Administration (3)
- Frontier Airlines (1)
- National Aeronautics and Space Administration (2)

- Pacific Southwest Airlines (1)
- Pan American World Airways (2)
- Piedmont Aviation (4)
- Trans World Airlines (6)
- United Airlines (31)
- United Technologies (2)
- Western Airlines (8)

The participating pilots could be classified as follows:

- Captain (35)
- First Officer (21)
- Second Officer (5)
- Management (6)
- Other (7)

Of the 74 pilots, 58 are currently B-727-rated. The remaining 16 (all previously B-727-qualified) are currently flying B-737, B-747, DC-8, or DC-10 aircraft. The pilots had an average of more than 10,000 hours' flying experience of which 500 hours were flown in the past year. Each pilot received an advance briefing packet (Appendix B) to familarize himself with the experiment.

3.4 SCENARIOS

The scenarios were selected for this experiment to permit evaluation of crew reaction in a realistic flight situation. Each scenario includes all phases of flight: departure, climb, en route, descent, and approach. Six scenarios were used, with flights departing Los Angeles International Airport using standard ATC procedures and, after a mid-course turn-around, receiving clearance back to Los Angeles for an approach and landing. Each of the six scenarios describes a flight of about 35 minutes. The flight plan information was presented to the crew before the experiment started.

Background traffic was included in each scenario to provide a realistic environment in the vicinity of the cockpit simulator. The background traffic used in the simulation was not intended to represent maximum current or projected traffic densities in the entire Los Angeles area. These aircraft were preprogrammed to fly typical IFR (Instrument Flight Rules) and VFR (Visual Flight Rules) flight paths around Los Angeles airport. Altitudes and flight paths were set so that some of the aircraft would appear in the computer-generated visual scene. While conflicts between the simulator and the background aircraft were not planned, some did occur as a result of variations in the way the subject pilots flew the simulator and responded to commands. Generally, situations developed where the background aircraft

was visible in the cockpit visual scene but was not considered a threat. Traffic advisories were sometimes presented on background aircraft without a subsequent command. This type of environment minimized the likelihood of the crews immediately interpreting each aircraft displayed as a threat.

Six intruders were encountered in each flight, each representing a different conflict geometry. A similar set of conflict geometries was used in all flights; however, the sequence in which they were presented was varied to realistically accommodate the specific flight path. The intruders were not equipped with ASA displays and therefore did not respond to the conflict situation. The scenarios are described briefly in the next few sections and in detail in Appendix A. The specific conflict geometries used also appear in Appendix A.

3.4.1 Scenario 1: Los Angeles to Las Vegas

After departure on runway 25R, the simulator is vectored westbound over the ocean until it reaches 6,000 feet, where it is turned to the departure track and will intercept V210 to Las Vegas in the vicinity of Meant Intersection. The first conflict occurs in the turn, with an aircraft heading eastbound on V299 descending through the simulator's cleared altitude of 6,000 feet.

Following resolution of this conflict, the simulator is vectored toward Meant and cleared to climb to its cruising altitude of FL190. During the climb, two additional conflicts are presented. When the simulator arrives over Meant, it is vectored into the profile approach for runway 24R. One conflict is presented during the vector, and two additional conflicts are presented on the final approach. One of these conflicts simulates an overshoot on a parallel ILS (Instrument Landing System) approach.

3.4.2 Scenario 2: Los Angeles to San Diego

The simulator departs runway 6L and climbs to 4,000 feet. A head-on conflict develops with an intruder on the 24R localizer, level at 4000 feet. The simulator is vectored direct to Seal Beach VOR (SLI), departing on a 148° radial to intercept V25 and cleared to its cruising altitude of 16,000 feet. Conflicts occur at SLI and at the turn onto V25 with intruders on V8 and V25, respectively. The simulator proceeds to Pacific Intersection, where it receives radar vectors to V23 inbound to SLI. Two additional conflicts occur on this leg. The simulator receives vectors for an ILS approach to runway 24R. The last conflict occurs on final approach.

3.4.3 Scenario 3: Los Angeles to Bakersfield

The simulator departs runway 25L and is vectored westbound over the ocean after being cleared to FL180. The first conflict occurs on this westbound leg. After the conflict is resolved, the simulator is vectored to intercept V23 to Gorman VOR (GMN) and cleared to its cruise altitude of FL180. Two additional conflicts occur before it reaches GMN, where it is

vectored to intercept V299 to Fillmore VOR (FIM). One conflict is generated on this leg. After FIM, the simulator is vectored via Mud Intersection for an ILS runway 6L approach. Two conflicts are generated during this phase, one involving a parallel ILS approach.

3.4.4 Scenario 4: Los Angeles to Las Vegas

The simulator departs runway 7R and after an initial climb is vectored to intercept V165. The first conflict occurs when the simulator crosses V201. The simulator is subsequently cleared to its cruise altitude of FL180 and proceeds to Palmdale VOR (PMD) via V165 and V518, with one conflict occurring on each airway. At PMD, the simulator is given a tear drop turnaround to intercept V197 to Pomona VOR (POM). Two additional conflicts occur on V197. At POM, the simulator is issued radar vectors to intercept the ILS for runway 25L. An intruder is attempting a simultaneous approach to runway 25R and causes a conflict.

3.4.5 Scenario 5: Los Angeles to Santa Barbara

The simulator departs runway 7R and is vectored south of the airport to intercept V25 at Exert Intersection. One conflict occurs as the simulator crosses V201, and another occurs just before Exert. After Exert, the simulator is cleared to its cruise altitude of 14,000 feet. The simulator proceeds along V25 through VTU and continues toward Santa Barbara VOR (SBA). At this point, a course reversal is issued that takes the simulator along V12S to FIM, outbound from FIM on the 158° radial to intercept the ILS approach course for runway 6L. Conflicts occur during the turn to intercept V12S, along V12S, on the 158° radial from FIM, and on final approach.

3.4.6 Scenario 6: Los Angeles to San Diego

The simulator departs on runway 25L and is vectored to intercept V25. A conflict occurs when the simulator crosses V201. The simulator is cleared to a cruise altitude of 14,000 feet as it proceeds along V25. Another conflict occurs on this leg. A course-reversal is issued before the simulator reaches Pacific Intersection. Vectors are issued to intercept V23 to SLI, depart SLI on the 251° radial for an ILS approach to runway 6L. Conflicts occur on V23, on the SLI 251° radial, at the turn toward the ILS localizer course, and at localizer interception.

3.5 TEST PERSONNEL AND EXPERIMENTAL PROCEDURES

In addition to the flight crew, four people were required to conduct a simulation session. There were two test observers, one for each simulation session, each having the same responsibilities. The other personnel consisted of a simulation controller and an air traffic controller. The functions of each of these people during a typical simulation session are described in the following subsections, and their normal positions are shown in Figure 3-1. Experimental procedures are described in the context of the functional descriptions of the test personnel.

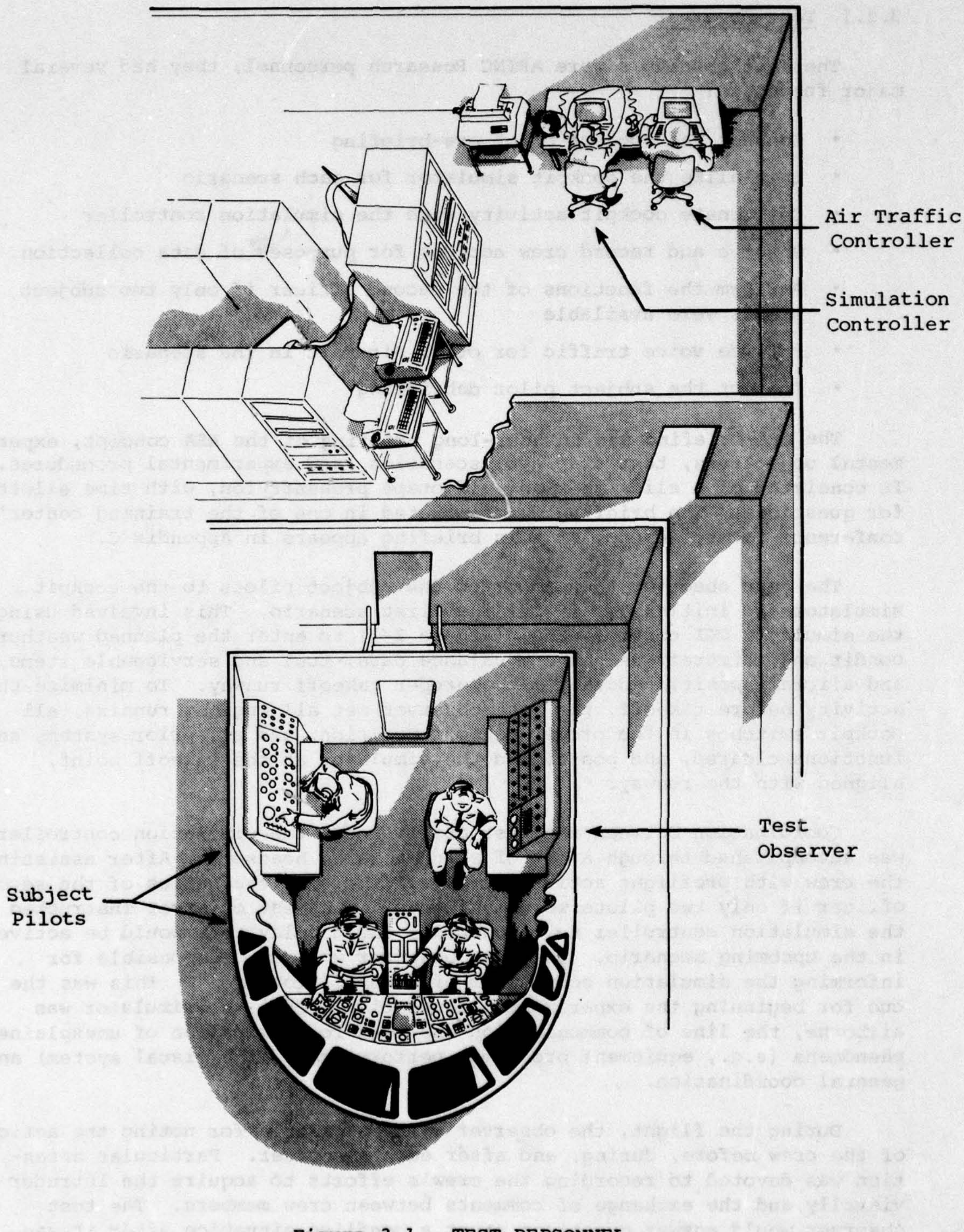

Figure 3-1. **TEST PERSONNEL**

3.5.1 Test Observer

The test observers were ARINC Research personnel; they had several major functions:

- Conduct the subject pilot pre-briefing
- Initialize the cockpit simulator for each scenario
- Coordinate cockpit activity with the simulation controller
- Observe and record crew actions for purposes of data collection
- Perform the functions of the second officer if only two subject pilots were available
- Provide voice traffic for other aircraft in the scenario
- Conduct the subject pilot debriefing

The pre-briefing was an hour-long briefing of the ASA concept, experimental objectives, test displays, scenarios, and experimental procedures. It consisted of a slide show and videotape presentation, with time allotted for questions. The briefing was conducted in one of the training center's conference rooms. A copy of this briefing appears in Appendix C.

The test observer then escorted the subject pilots to the cockpit simulator and initialized it for the first scenario. This involved using the simulator CGI control panel (Figure 2-1) to enter the planned weather conditions, aircraft weight and balance data, fuel and serviceable items, and aircraft position data for the proper takeoff runway. To minimize the activity before takeoff, the test observer set all engines running, all cockpit switches in the proper takeoff position, and all prior systems and functions cleared, and positioned the simulator at the takeoff point, aligned with the runway.

Coordination between the test observer and the simulation controller was accomplished through a set of sound-powered headsets. After assisting the crew with preflight activities (which included the duties of the second officer if only two pilots were available), the test observer instructed the simulation controller to demonstrate the display that would be active in the upcoming scenario. The test observer was also responsible for informing the simulation controller of takeoff "rotation". This was the cue for beginning the experimental simulation. Once the simulator was airborne, the line of communication was used for discussion of unexplained phenomena (e.g., equipment problems, performance of the visual system) and general coordination.

During the flight, the observer was responsible for noting the actions of the crew before, during, and after each encounter. Particular attention was devoted to recording the crew's efforts to acquire the intruder visually and the exchange of comments between crew members. The test observer would answer questions about a conflict situation after it was resolved but would not help the pilots interpret the ASA displays.

When the workload permitted, the test observer provided voice traffic on the ATC frequency. This background traffic was coordinated with the air traffic controller and represented realistic transmissions for aircraft flying in the Los Angeles area. As a result, the subject pilots were often unable to talk immediately with the air traffic controller during conflict situations because of heavy voice traffic.

After the session was completed, the test observer conducted the subject pilots back to the conference room for a debriefing. The debriefing consisted of a written questionnaire followed by a discussion of the experiment. The test observer had the responsibility for answering questions about the questionnaire and leading the discussion that followed. The test observer used the notes accumulated during the session to add to the discussion.

Two test observers were required to handle the back-to-back scheduling of simulator time. A typical schedule appears in Figure 3-2.

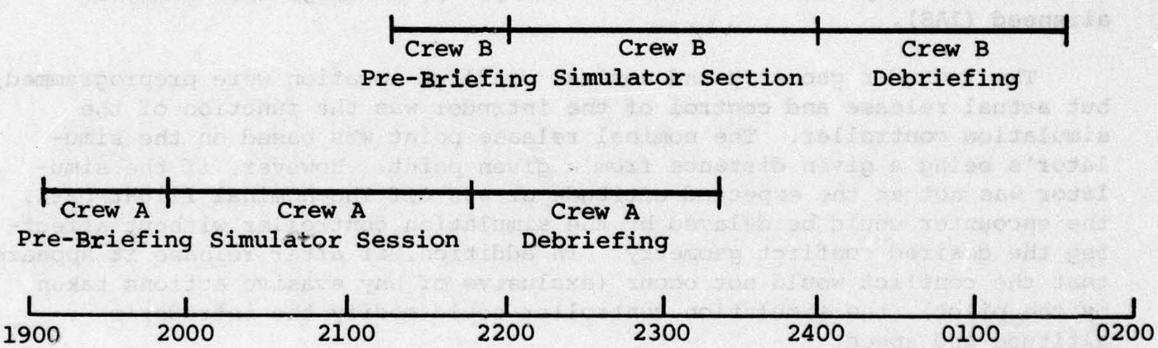

Figure 3-2. TYPICAL CREW SCHEDULING

When time permitted, the second test observer assisted in providing background voice traffic.

3.5.2 Simulation Controller

The simulation controller, an ARINC Research employee, had the following functions:

- Experimental setup and checkout
- Interaction with the simulation software
- Coordination with the air traffic controller
- Management of data recording equipment and material

Before each simulation session, the simulation controller was responsible for setting up and checking out the simulation control computer, the CGI computer, and the communications links between the simulator and the

control/monitor station. As soon as the simulator was available, the simulation controller coordinated with United Airlines maintenance personnel for installation, power up, and checkout of the ASA displays. At "rotation," the simulation controller initiated the ASA simulation.

The simulation controller was the simulation's computer operator and conducted all of the interaction with the computers. The interactive functions included the following:

- Obtaining information about aircraft active in the scenario
- Releasing and controlling intruder aircraft
- Rescaling the ATC display
- Changing the ASA mode of operation

To augment the information presented on the air traffic controller's display, the simulation controller could request additional information on aircraft active in the scenario (including the simulator). This information includes position coordinates (x, y, z), heading, and indicated airspeed (IAS).

The intruder geometry and nominal conflict location were preprogrammed, but actual release and control of the intruder was the function of the simulation controller. The nominal release point was based on the simulator's being a given distance from a given point. However, if the simulator was not at the expected altitude or was off the nominal flight path, the encounter could be delayed by the simulation controller without affecting the desired conflict geometry. In addition, if after release it appeared that the conflict would not occur (exclusive of any evasive actions taken by the pilot), the simulation controller could modify the intruder's altitude and speed.

Coordination with the air traffic controller included the functions mentioned above as well as keeping the controller abreast of upcoming events in the scenario and relaying messages from the test observer.

Data recording was for the most part automatic. The simulation controller was responsible for mounting tapes, transferring data from disk to tape, and documenting the recorded data.

3.5.3 Air Traffic Controller

The air traffic controller who participated in the experiment was Chester MacMillan, an 8-year veteran of the FAA. Mr. MacMillan is a Plans and Procedures Specialist with the Rocky Mountain Region and was involved in the experimental metering and spacing and profile descent programs operated at Denver.

The air traffic controller's primary function was to provide control for the cockpit simulator and provide background voice traffic for other simulated aircraft. The controller simulated all of the ATC positions -- clearance delivery, tower, departure, en route, and approach -- and

simulated handoffs between the positions. The subject pilots received all of the clearances that they would normally receive in a typical flight around Los Angeles. The nominal clearances given for each of the six scenarios appear in Appendix A.

The controller was also responsible for ensuring that the conflict situations developed as planned. This would sometimes require the controller to issue special clearances to maneuver the simulator into position.

The controller was assisted by the test observer and was presented with a plan view of the traffic situation (Figure 3-3). This graphical presentation was displayed on a storage tube device and included appropriate airways, fixes, aircraft tracks, and a readout of simulator altitude (in hundreds of feet). Aircraft were represented by letters to distinguish the tracks. The simulator was always aircraft "K". The display would automatically redraw and center the simulator when its path approached the edge of the viewing area. This rescaling could also be accomplished on request.

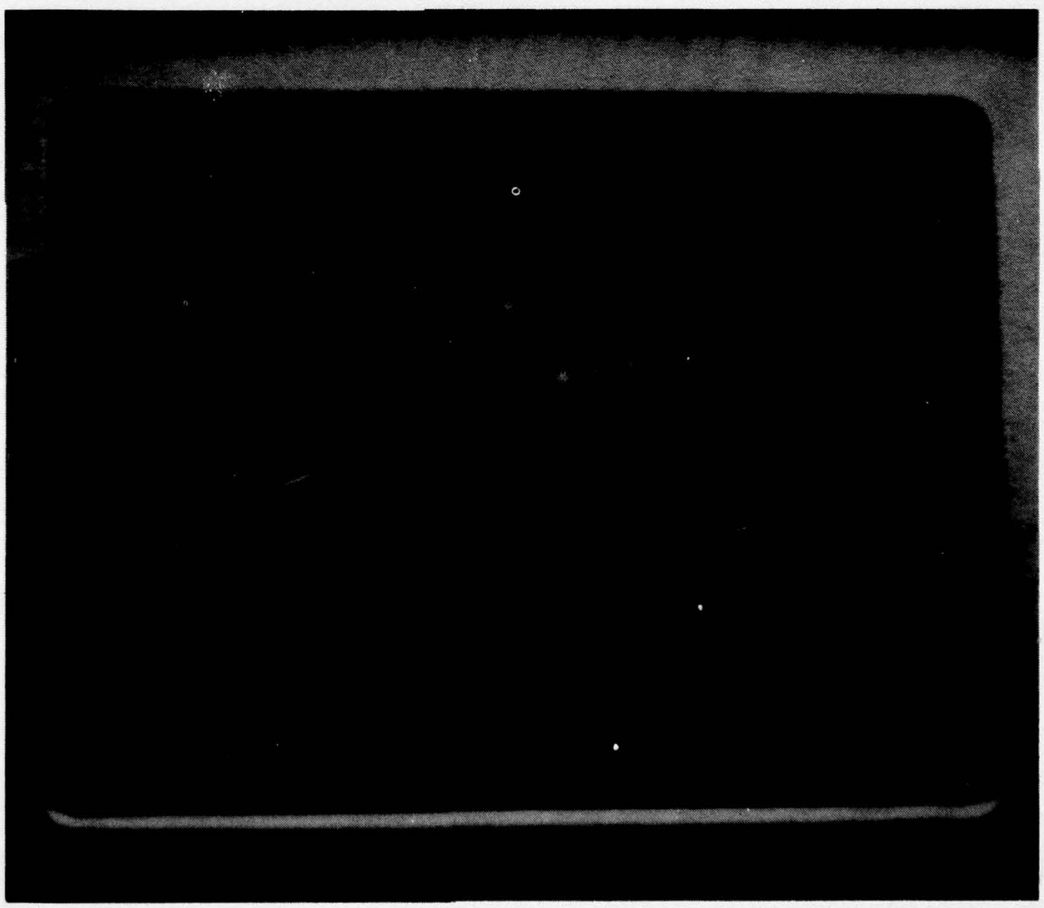

Figure 3-3. AIR TRAFFIC CONTROLLER DISPLAY

CHAPTER FOUR

QUALITATIVE DATA ANALYSIS

The subjective evaluations of the pilot population can be as decisive as the technical measurements of the system in determining the acceptability of the ASA concepts. Therefore, a subjective, or qualitative, analysis was performed as part of the simulation evaluation. The data collected were in the form of questionnaires and debriefing comments.

4.1 DATA COLLECTION PROCEDURES

Immediately following the simulator test session, the subject pilots were asked to fill out a lengthy questionnaire that included questions on pilot background, quality of displayed commands, display characteristics, display usability, traffic advisories, command presentation, ASA concepts, display evaluation, and the ASA program.

After completing the questionnaire, the pilots were subjected to a debriefing session in which several issues were probed more deeply, and the pilots were asked to provide additional comments on any aspect of the simulation or ASA concept that they desired. The discussion was led by the test observer, who used his observations during the simulation to stimulate the conversation. Issues that were discussed in all of the sessions included preference for horizontal versus vertical maneuvers, additional flight testing, realism of the visual scene, use of the color red for collision avoidance commands, comparisons of active versus full mode, relative versus absolute data presentations, value of the vertical speed limit commands, and the role of the ASA system in the operational environment.

The original questionnaire data were supplemented by a follow-up questionnaire approximately 2 1/2 months after the close of testing. The second questionnaire was developed to help clarify some of the questions that were previously asked. In addition, pilots were solicited for addi-ional comments and changed opinions. The questionnaires are reproduced .n Appendixes D and E.

4.2 QUESTIONNAIRE ORGANIZATION

The initial questionnaire consisted of 53 questions distributed among the following subject areas:

- Subject pilot background
- Test display evaluation
- Information content of an ASA display
- Impact of introduction of ASA on flight and ATC procedures

All 74 subject pilots filled out a questionnaire. However, the first three crews (10 subject pilots) filled out a shorter version. Discussions with the FAA led to the more complete version given to the remaining crews.

The type of questions asked in the questionnaire included multiple choice, yes and no, single answer, and brief comments. In addition, comments were solicited on any of the questions to which the pilots wished to respond. In explaining the results, this report employs some of those comments.

The supplemental questionnaire has a format similar to that of the initial questionnaire. The questions were designed to clarify previously asked questions and to verify that the questions were properly understood. Several questions were included to determine if pilot opinion had changed in the 2-1/2 months since the close of testing. The supplemental questionnaire was mailed to all 74 subject pilots, and 50 responded.

4.3 ANALYSIS METHODOLOGY

The analysis of the questionnaire data involved tabulation of the responses. Since the underlying distributions of the data are unknown because of the nonquantifiable nature of the responses, a nonparametric (i.e., distribution-free) statistical analysis approach was applied to evaluate the data. The nonparametric methods are based on the relative ranking of the responses (least to greatest) as a replacement for actual numerical measurements of the type used in classical statistical methods.

The following factors were considered in the analysis as having influence on the results:

- Position (captain, first officer, and second officer)
- Currency (currently B-727-rated)
- Familiarity with United B-727 simulator
- Familiarity with Los Angeles airspace
- Subject pilot selection (recommended by airline management or Air Line Pilots Association)
- Display preference

Position is related to the crew's experience since airline captains usually have more flying hours than first or second officers. Familiarity with the B-727, the United simulator, and the Los Angeles airspace have an impact on the pilot's ability to fly the simulator and therefore may affect his performance in a conflict situation. Subject pilot selection is treated as a factor to ensure that the results were not overly influenced by either airline management's or ALPA's point of view. Display preference is used as a factor to eliminate any preconceived bias toward any of the displays used.

4.4 QUALITATIVE RESULTS

The results are illustrated in bar chart form. Each chart represents a particular topic and presents the questions and possible responses exactly as they appeared in the subject questionnaires. The results are presented as a percentage of those pilots responding to the question. The actual number of pilots responding follows in parentheses. Since some questions were left unanswered, comparisons between responses should be made by comparing percentage responding as opposed to number responding.

4.4.1 Test Display Evaluation

This section addresses test display physical characteristics such as readability and understandability, use of color, displayed range, alerting features, and display format. It also examines test display preference and suggested alternatives. While the questions asked were related primarily to the test displays, conclusions can be drawn about features that would be desirable or undesirable in a generic display.

4.4.1.1 Readability and Understandability

The questions on readability served the purpose of substantiating that the selected test displays were of an acceptable test quality and that the presentation was understood. This was confirmed by the subject pilots. More than 80 percent of the pilots felt that the three displays were usually or always readable and understandable. These results were generally uniform over the possible commands, but there were some problems with presentation of "No Turn" and "Limit Climb" commands on the IVSI. The limit-climb bars were obscured somewhat by the top of the instrument case because of the angle at which the instrument was viewed, and the placement of the lights for the "No Turn" indicators was insufficient for total illumination. Other comments reflected the difference in intensity between the two LED displays. These two prototype instruments were identical in format; however, one instrument was designed for both daylight and night applications and the other for low ambient light applications. On the CRT display, the problems concerned the obstruction of the lower left portion of the CRT by the speed brake lever; this would block parts of the negative and limit commands ("Don't" and "Limit") when viewed from the captain's position.

4.4.1.2 Use of Color

The IVSI used two colors in its presentation -- red for positive commands and yellow for negative and limit vertical commands. The LED used those colors and added green for traffic advisories. The CRT display was monochromatic.

The subject pilots were asked to give their reactions to the use of color in the IVSI and LED and to the proposal for using color in the CRT. The responses favored its use, as illustrated in Figure 4-1. In addition, the use of color was suggested as an alternative to "filling in" the intruder symbol on the CRT as a means of differentiating between the PWIs and actual threats.

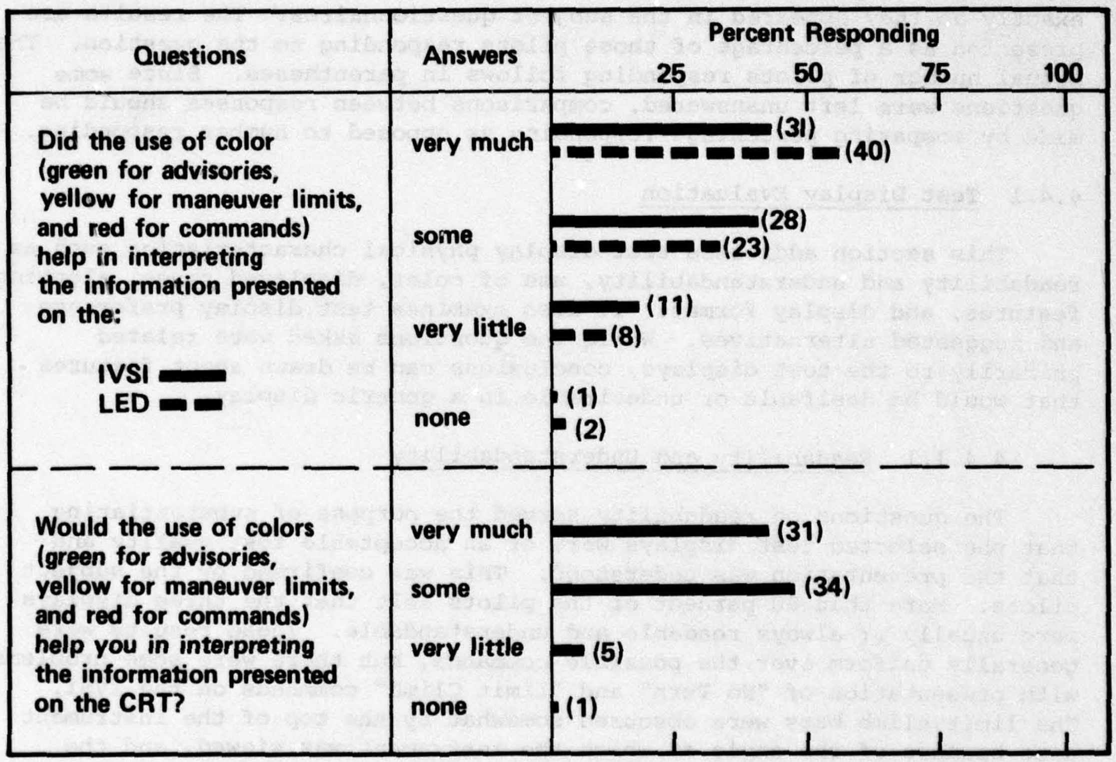

Figure 4-1. USE OF COLOR

The issue of using red in an ASA display to indicate a positive action was focused on in the debriefing. The vast majority of crews felt that red was used appropriately in the experimental displays, a few felt that it was an important feature, and others objected slightly but felt that proper training would eliminate any problems. Very few voiced strong objections.

Those who objected cited the traditional connotation of red in a display to stop a particular action and not to indicate a positive action.

4.4.1.3 Displayed Range

Only the LED and CRT displays presented range information on other aircraft. The LED displayed range as part of the traffic advisory message and presented it as a two-digit integer representing the number of nautical miles from the simulator. The CRT had two presentations for range. In full mode, range rings divided the display area at 3-nautical mile and 6-nautical mile intervals from the simulator, with a maximum displayed range of 9 miles ahead and 6 miles behind and on both sides. In active mode, range was presented as a number accurate to tenths of a mile.

Responses to the questionnaire indicated that the pilots were for the most part satisfied with the range, as illustrated in Figure 4-2. Comments suggested a multiple scale on the CRT that could be adjusted in flight.

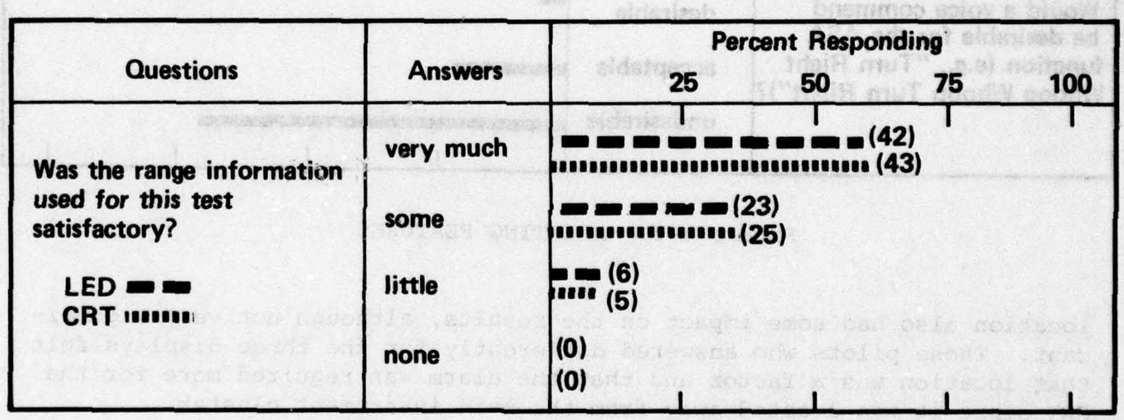

Figure 4-2. DISPLAYABLE RANGE

4.4.1.4 Alerting Features

The primary alerting feature for all three of the tested displays was a 2-second tone burst (1 kHz square wave). The alarm was sounded whenever a new limit, negative, or positive command was presented on the display.

Two questions were asked about alerting features, the results of which are presented in Figure 4-3. A general comment indicated that the alarm could have been louder (one pilot said that he never heard the alarm).

Comments from those that answered negatively on the necessity of an audio alert restricted their answer to a nighttime scenario. Many felt that during the daylight hours the alert would be more important. Display

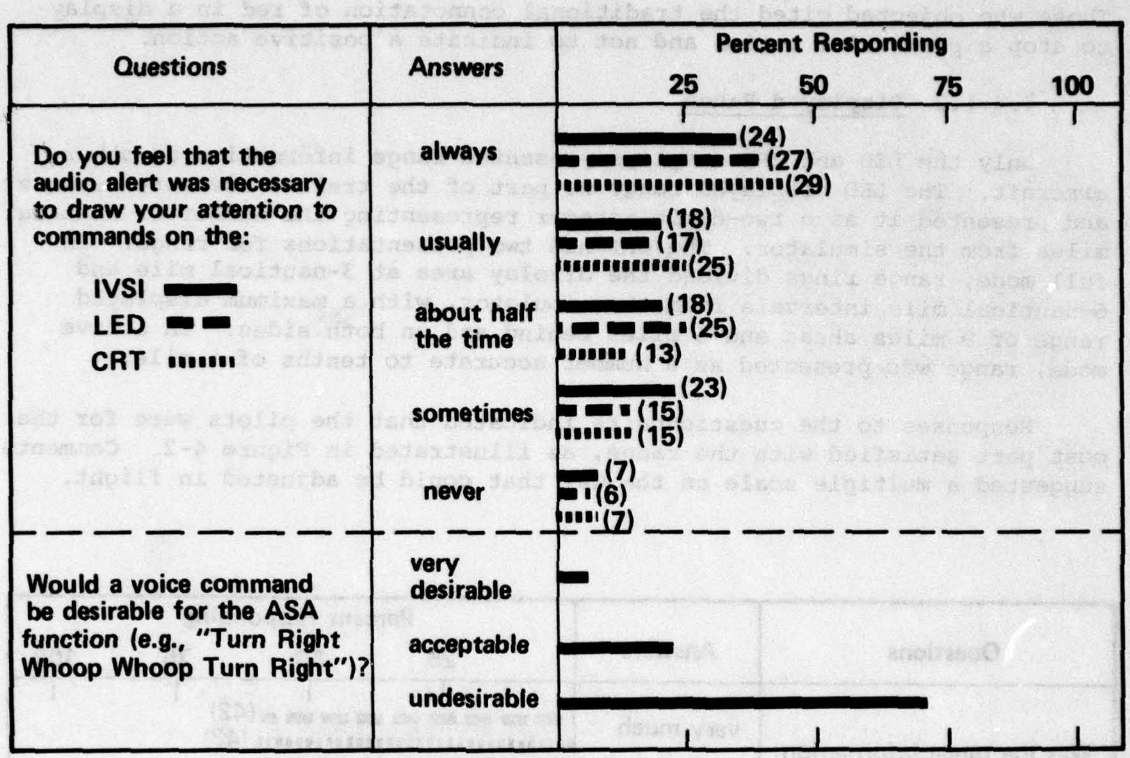

Figure 4-3. ALERTING FEATURES

location also had some impact on the results, although not very significant. Those pilots who answered differently for the three displays felt that location was a factor and that the alarm was required more for the CRT since it was located away from the main instrument cluster.

The responses to the voice command option may have been biased because of the unfortunate use of the phrase "whoop whoop" in the example. Many pilots instantly related the voice command to the ground proximity warning system installed aboard all aircraft. This device, as initially installed, produced a large number of false alarms and therefore was not well received by pilots.

Other comments related to the negative aspects of startling alarms are as follows:

"Startle factor temporarily prevents any action."

"The more annoying, the longer it takes to recover one's thought process."

"Crew reaction is to disable warning rather than solve the problem (Fire/GPWS Warning Bell)."

"Even very loud/annoying alerts can be mentally tuned out or disregarded/ ignored."

A secondary alerting factor is related to the visual cues produced by a newly displayed command. This feature was accentuated by the nighttime simulation and benefited the IVSI most, the LED somewhat, and the CRT least. Location of the display is the dominant factor, although intensity and contrast levels have a significant effect.

4.4.1.5 Display Format

This section presents display-format comments not discussed in the previous sections.

A specific format item investigated was the presentation of positive commands on an ASA display. The pilots had been presented with arrows only (IVSI)*, arrows and text (LED), and text only (CRT). The results showed that 25 percent of the subject pilots preferred text only, 41 percent preferred arrows only, and the remaining 34 percent preferred a combination of text and arrows.

Other comments were specific to the formats actually used in the experiment. Several comments illustrated concern over the LED presentation of traffic advisories. Many felt that the format required too much interpretation and that the display was too busy when multiple traffic advisories were presented. There were also some problems with interpreting the traffic advisories. Pilots would confuse the order in which the information was presented and forget the units in which the information was measured.

The most common complaint about the CRT display was the small size of the symbology used (0.10" x 0.14") for the aircraft alphanumeric tags. The size was a limitation of the electronics and was related to the available dot size. Other comments suggested moving the alphanumeric tag away from the aircraft symbol and trail for improved readability.

Many pilots commented on the active mode format for the CRT. They felt that there was too much wording on the display and that no wording was required in nonthreatening situations.

4.4.1.6 Test Display Preference

This section examines the subject pilots' preferences for the test displays used in the experiment. Since the field of test displays included only three representatives, the results presented in this section should be interpreted as a preference for a display presentation (lighted indicators, alphanumerics, and pictorial display with alphanumerics) or for information content (commands only, commands with alphanumeric traffic

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*The IVSI is considered an arrows-only presentation because the lettering on the arrows is judged to be too small to interpret quickly.

advisories, and commands with a pictorial traffic situation). The results should not be interpreted as a recommendation for implementing one of the test displays.

The subject pilots were asked to rate the displays in order of preference based on the simulation session. The results are shown in Figure 4-4. While the results are not overwhelmingly in favor of any particular display, there is a definite preference for the CRT display. The LED display was ranked second and the IVSI third in overall preference. However, as illustrated in Figure 4-5, any of the three displays would be acceptable to a large percentage of the sampled pilot population (more than 73 percent).

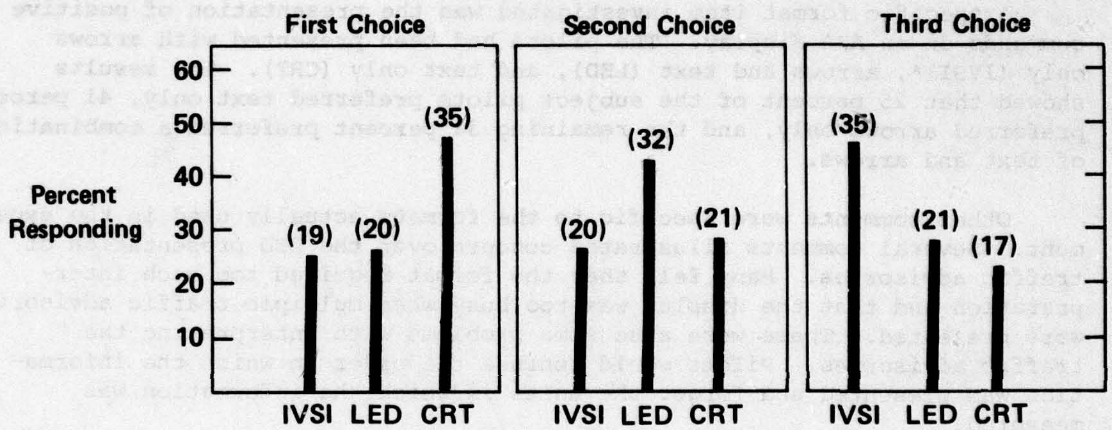


Figure 4-4. TEST DISPLAY PREFERENCE (OVERALL)
(ORIGINAL QUESTIONNAIRE)

The data were categorized to determine the effect of the sponsoring organization on the results. The two categories are pilots recommended by the Air Line Pilots Association (ALPA) and pilots recommended by airline management. The results are presented in Figures 4-6 and 4-7. The management-recommended pilots were somewhat evenly distributed with regard to display preference although the ranking remained the same as in the overall breakdown. The ALPA-recommended pilots also indicated the same ranking.

A further breakdown of display preference by pilot experience (captains versus first officers) was also performed. Again, the results (Figures 4-8 and 4-9) indicated basically the same preferences.

Similar display-preference questions were asked in the supplemental questionnaire; the results are shown in Figures 4-10 and 4-11. The questions were restricted to the active mode environment, where bearing information was not available. The questions also suggested that the

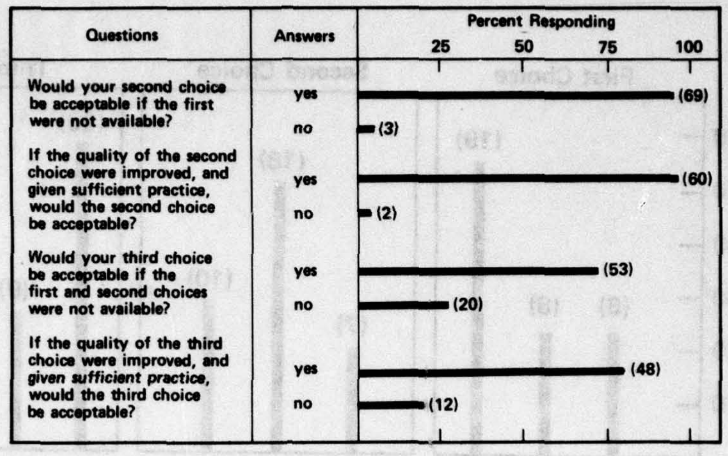


Figure 4-5. ACCEPTABILITY OF SECOND AND THIRD CHOICES (ORIGINAL QUESTIONNAIRE)

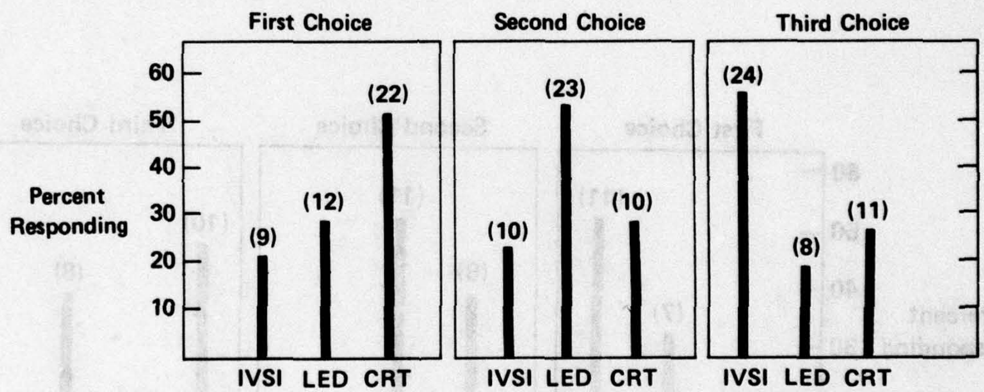


Figure 4-6. TEST DISPLAY PREFERENCE (ALPA - RECOMMENDED PILOTS)

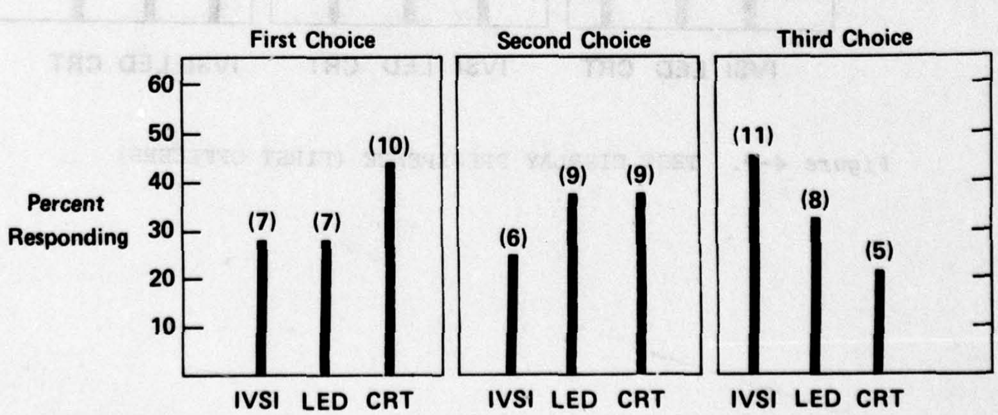


Figure 4-7. TEST DISPLAY PREFERENCE (MANAGEMENT - RECOMMENDED PILOTS)

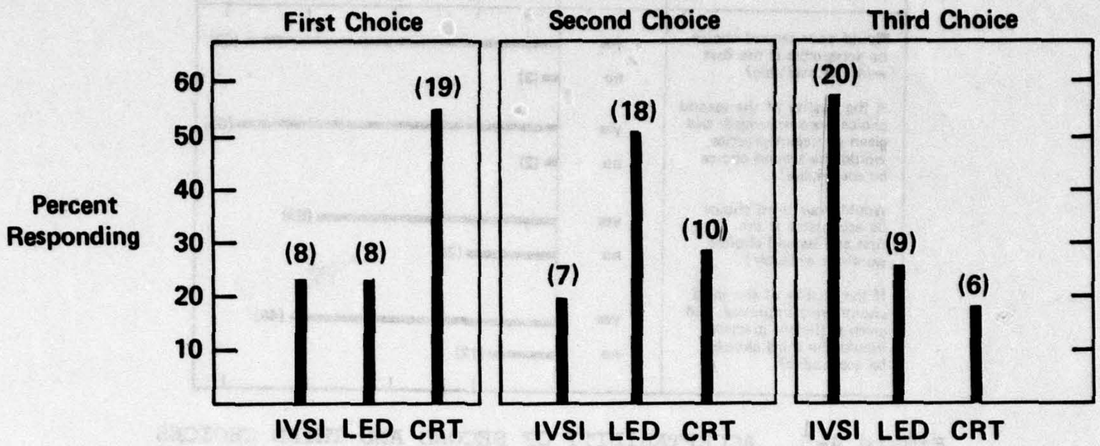


Figure 4-8. TEST DISPLAY PREFERENCE (CAPTAINS)

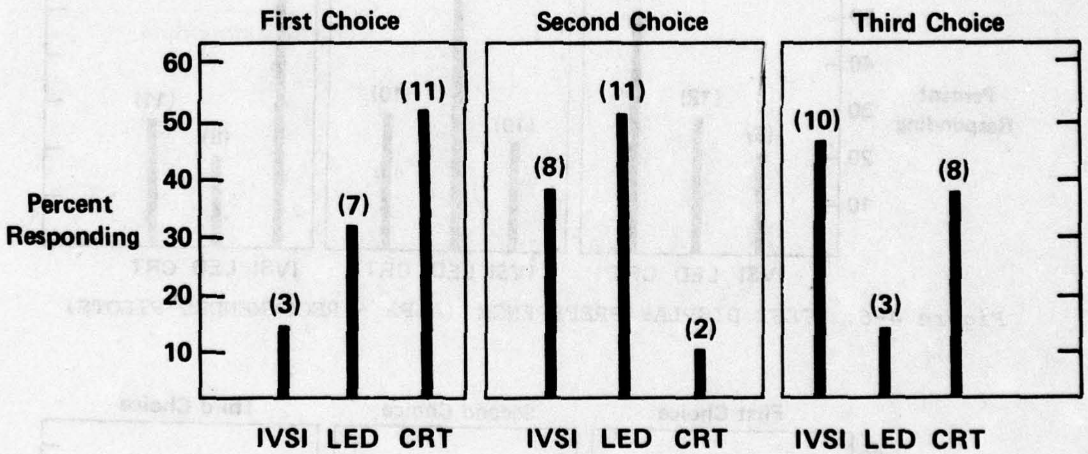


Figure 4-9. TEST DISPLAY PREFERENCE (FIRST OFFICERS)

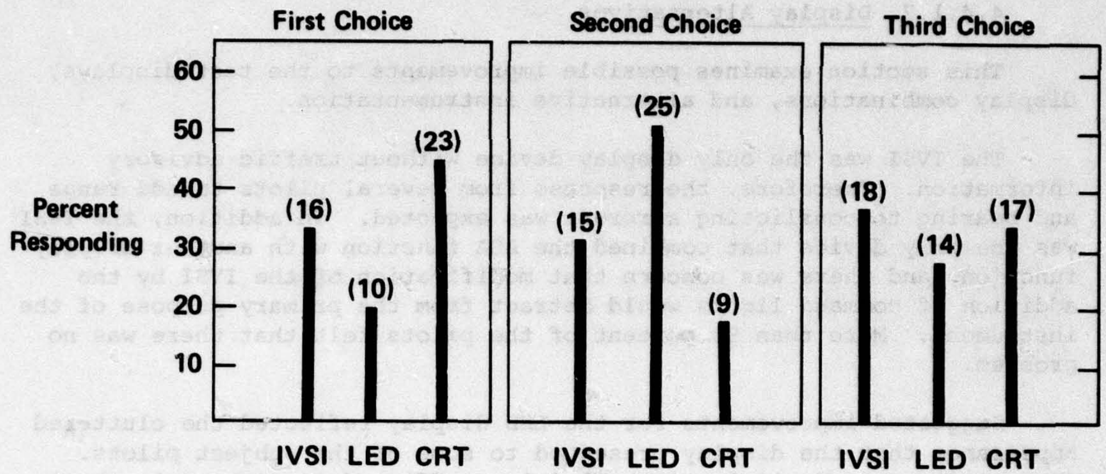


Figure 4-10. TEST DISPLAY PREFERENCE (OVERALL) (SUPPLEMENTAL QUESTIONNAIRE)

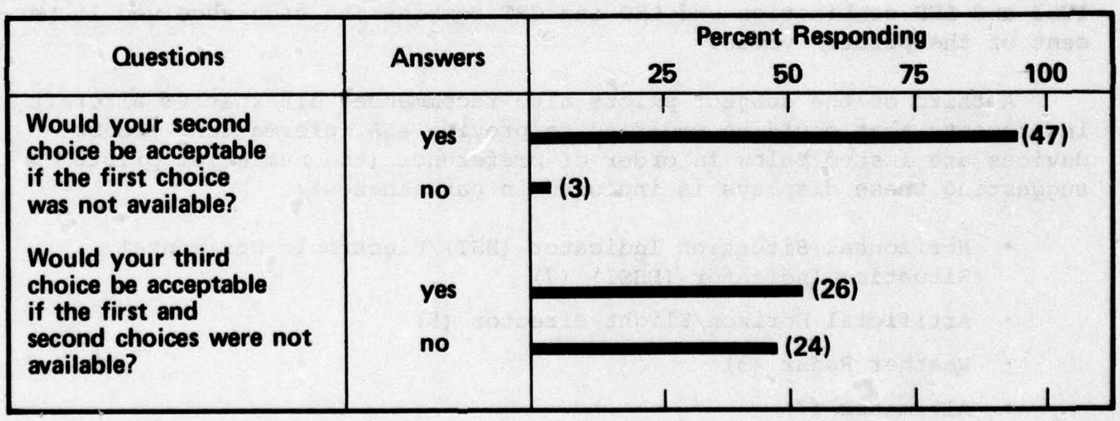


Figure 4-11. ACCEPTABILITY OF SECOND AND THIRD CHOICES (SUPPLEMENTAL QUESTIONNAIRE)

active mode representation on the CRT display would most probably be a graphical presentation rather than the alphanumeric presentation used in the tests.

The results still maintain the same overall ranking of the displays, with the CRT and LED displays losing some ground to the IVSI, making the results appear more uniformly distributed. In addition, there appeared to be much less acceptance of the pilots' third choice.

4.4.1.7 Display Alternatives

This section examines possible improvements to the test displays, display combinations, and alternative instrumentation.

The IVSI was the only display device without traffic advisory information. Therefore, the response from several pilots to add range and bearing to conflicting aircraft was expected. In addition, the IVSI was the only device that combined the ASA function with another display function, and there was concern that modification of the IVSI by the addition of command lights would detract from the primary purpose of the instrument. More than 90 percent of the pilots felt that there was no problem.

Suggested improvements for the LED display reflected the cluttered appearance that the display presented to some of the subject pilots. Comments suggested eliminating multiple traffic advisories, only showing the most important; and eliminating direction of flight from the advisory.

Combinations of displays were also suggested. More than 50 percent of the pilots responding felt that a combination of display devices would provide more usable information than the best test display. The IVSI and CRT combination was best received by 26 percent of the pilots, and the IVSI and LED combination and LED and CRT combination each received 15 percent of the pilots' votes.

A third of the subject pilots also recommended alternative aircraft instruments that could be modified to provide ASA information. These devices are listed below in order of preference (the number of pilots suggesting these displays is included in parentheses):

- Horizontal Situation Indicator (HSI)/Electronic Horizontal Situation Indicator (EHSI) (7)
- Artificial Horizon/Flight Director (5)
- Weather Radar (3)
- Altimeter (2)
- Vertical Speed Indicator (VSI)/Horizontal Situation Indicator (HSI) combination (2)
- Head-Up Display (HUD) (2)
- Radio Magnetic Indicator (RMI) (1)

4.4.2 Information Content of an ASA Display

This section addresses information elements that could be part of an ASA display. In addition, it examines the combination of those elements into traffic advisories and commands.

4.4.2.1 Information Elements

In the questionnaire, the subject pilots were presented with 11 collision avoidance information elements that they were asked to rank (1 to 11) in order of importance. They were also asked to check all elements that they considered to be an essential part of any collision avoidance display.

The results were tabulated and a composite rank for each element was produced. The composite rank was calculated as the sum of the rank values (1 to 11) selected by the pilots divided by the number of pilots responding. The elements are listed in Table 4-1 in order of rank (the value 1 indicates the highest rank) with their composite rank and the percentage of respondents that considered the information item essential to a collision avoidance display.

Table 4-1. RANKING OF INFORMATION ITEMS

Rank	Information Item	Composite Rank	Percent Responding "Essential"
1	Altitude of other aircraft	1.787	85
2	Range of other aircraft	2.686	81
3	Relative bearing	3.542	59
4	Heading of other aircraft	4.089	51
5	Horizontal closure rate	4.801	21
6	Vertical closure rate	5.524	17
7	Vertical speed of other aircraft	6.713	20
8	Projected miss distance	7.421	14
9	Closure angle	7.425	7
10	Other aircraft type	9.198	5
11	Other aircraft identity	10.052	3

These results show that altitude and range of the other aircraft are by far the most important information elements for a collision avoidance display. This information is available directly from the active mode ASA data base. Bearing and heading of other aircraft, third and fourth ranking, were considered essential by more than half of the subject pilots. This information is available only if the full mode ASA system is in use. The remaining elements were rated significantly lower and were considered much less critical to conflict resolution.

With the exception of altitude, all of the information elements could be clearly expressed in either relative or absolute terms, but not both. To determine the preferred representation of altitude information, a question was included in the questionnaire. The overwhelming majority (89 percent) favored an MSL or absolute representation versus a relative representation.

4.4.2.2 Traffic Advisories

Traffic advisories were presented on both the LED and CRT displays. The advisories were initiated by the ASA PWI logic. The logic defined a protected volume of airspace around an aircraft and identified those aircraft which violated it. The protected volume was defined with range, range rate, horizontal tau, altitude, altitude rate, and vertical tau criteria. Once displayed, the advisory remained visible for the amount of time the aircraft was within the protected volume; however, the display logic maintained the advisory for at least 30 seconds. This 30-second period was selected as a result of pre-test design evaluation. Advisories appearing for less than that time were considered distracting. Advisories were updated every second in active mode and every 4 seconds in full mode.

Up to three advisories could be displayed concurrently on the LED in nonconflict situations. When an ASA command was required, however, only the advisory for the aircraft involved in the conflict was displayed. The format for the LED traffic advisories is specified in Subsection 2.3.2.

The CRT display was capable of displaying all aircraft that violated the PWI criteria and fell within the range limitations of the display (9 miles forward and 6 miles behind and to both sides of own-aircraft). Typically, in the traffic environment used in the simulation, no more than three advisories were presented. However, occasionally more were presented. When an ASA command was presented, the symbol representing the aircraft involved in the conflict became solid. All other advisories remained displayed. The format for the CRT traffic advisories is described in Subsection 2.3.3.

There were a number of questions in the initial and supplemental questionnaires regarding traffic advisories. The results are presented in Figures 4-12 through 4-14.

Figure 4-12 illustrates the results of questions on the information content of traffic advisories. Most pilots felt that the advisories were presented in a useful format on both the LED and CRT displays, with many pilots feeling that more aircraft than necessary were sometimes displayed on the two devices. This was verified by a separate question requesting a recommended maximum number of simultaneously displayed advisories. Figure 4-13 illustrates the results. The average recommendation for the LED-type format was slightly less than 2.5 advisories, with a CRT-type recommendation of slightly greater than 3 advisories. This suggests that a pictorial presentation is simpler to understand; however, the CRT display area was several times larger than the display area for the LED, which permitted a less cluttered display. These data also reflect the pilot's inability to handle more than 2 or 3 simultaneous advisories.

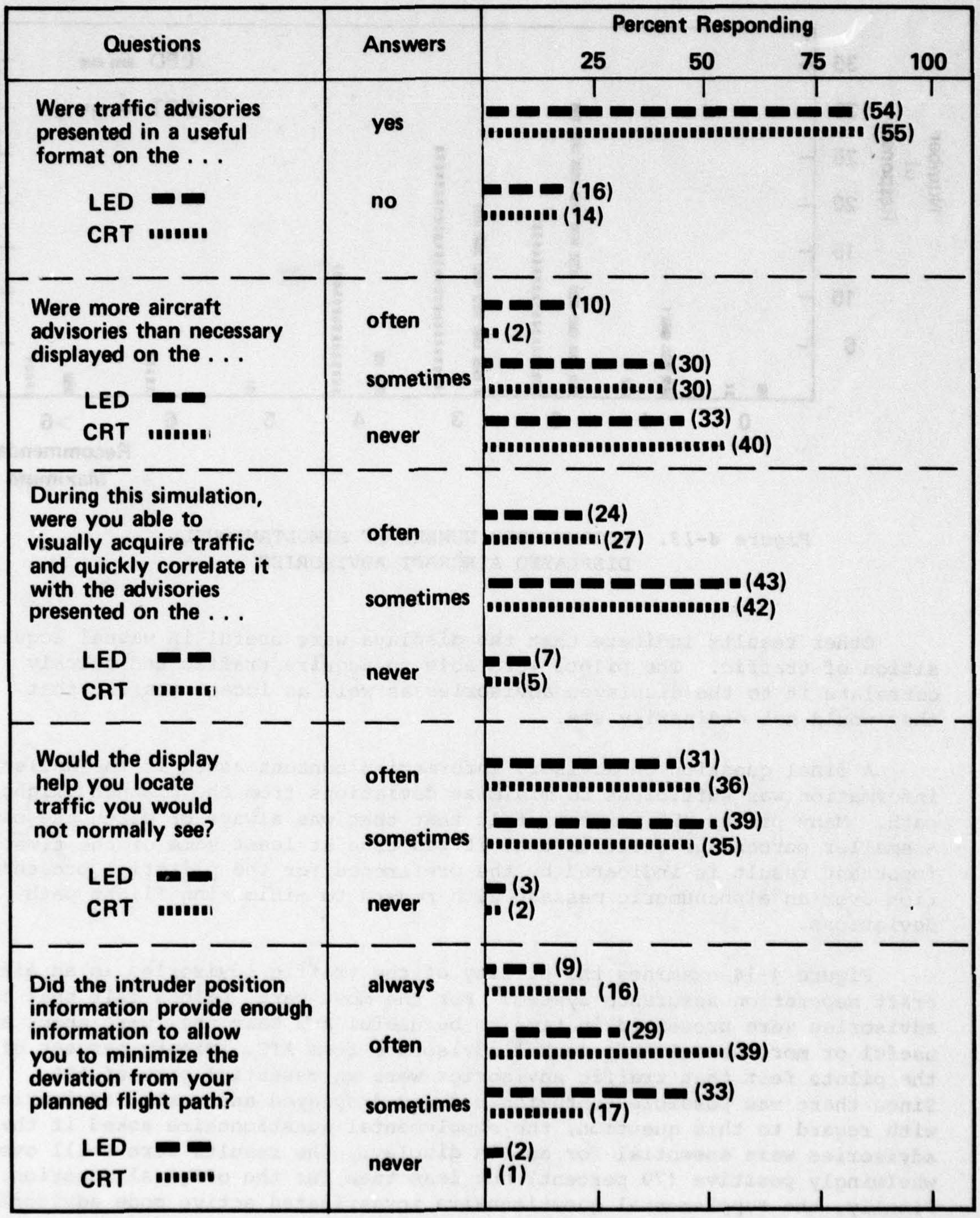


Figure 4-12. TRAFFIC ADVISORIES (INFORMATION CONTENT)

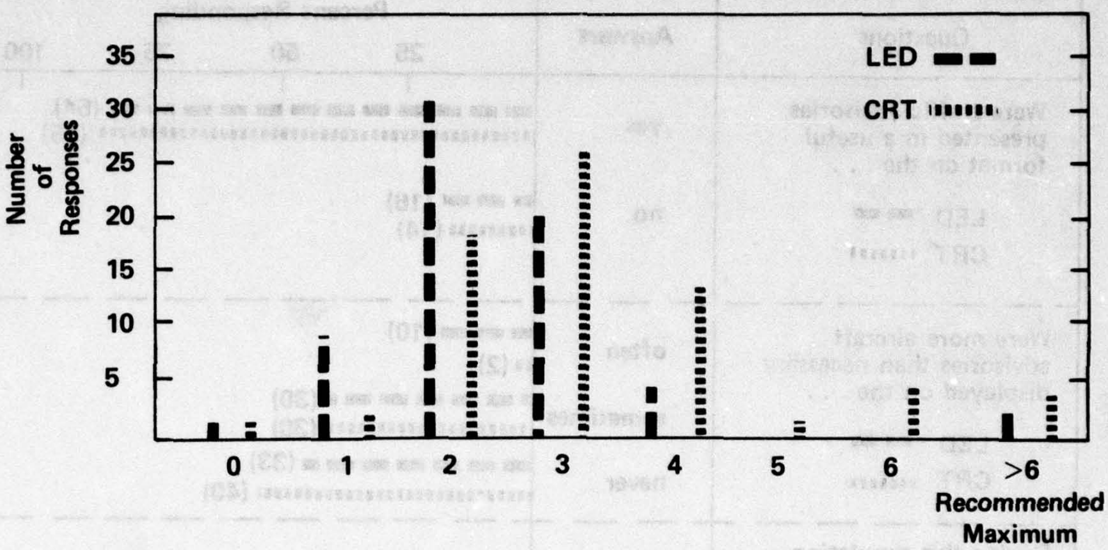


Figure 4-13. RECOMMENDED NUMBER OF SIMULTANEOUSLY DISPLAYED AIRCRAFT ADVISORIES

Other results indicate that the displays were useful in visual acquisition of traffic. The pilots were able to acquire traffic and quickly correlate it to the displayed advisories as well as locate traffic that they would not ordinarily see.

A final question on advisory information content asked if the advisory information was sufficient to minimize deviations from the planned flight path. Many pilots (75 percent) felt that that was always or often the case. A smaller percentage believed that it was true at least some of the time. The important result is indicated by the preference for the pictorial presentation over an alphanumeric message with regard to minimizing flight path deviations.

Figure 4-14 examines the utility of the traffic advisories in an aircraft separation assurance system. For the most part, pilots felt that the advisories were presented in time to be useful and that they were about as useful or more useful than verbal advisories from ATC. Ninety percent of the pilots felt that traffic advisories were an essential part of ASA. Since there was possible confusion between displayed and verbal advisories with regard to this question, the supplemental questionnaire asked if the advisories were essential for an ASA display. The results were still overwhelmingly positive (79 percent) but less than for the original question. Finally, the supplemental questionnaire investigated active mode advisories, and the results indicated the same positive attitude.

Discussions with the pilots provided insight into the problems associated with today's method of issuing traffic advisories. Pilots complained

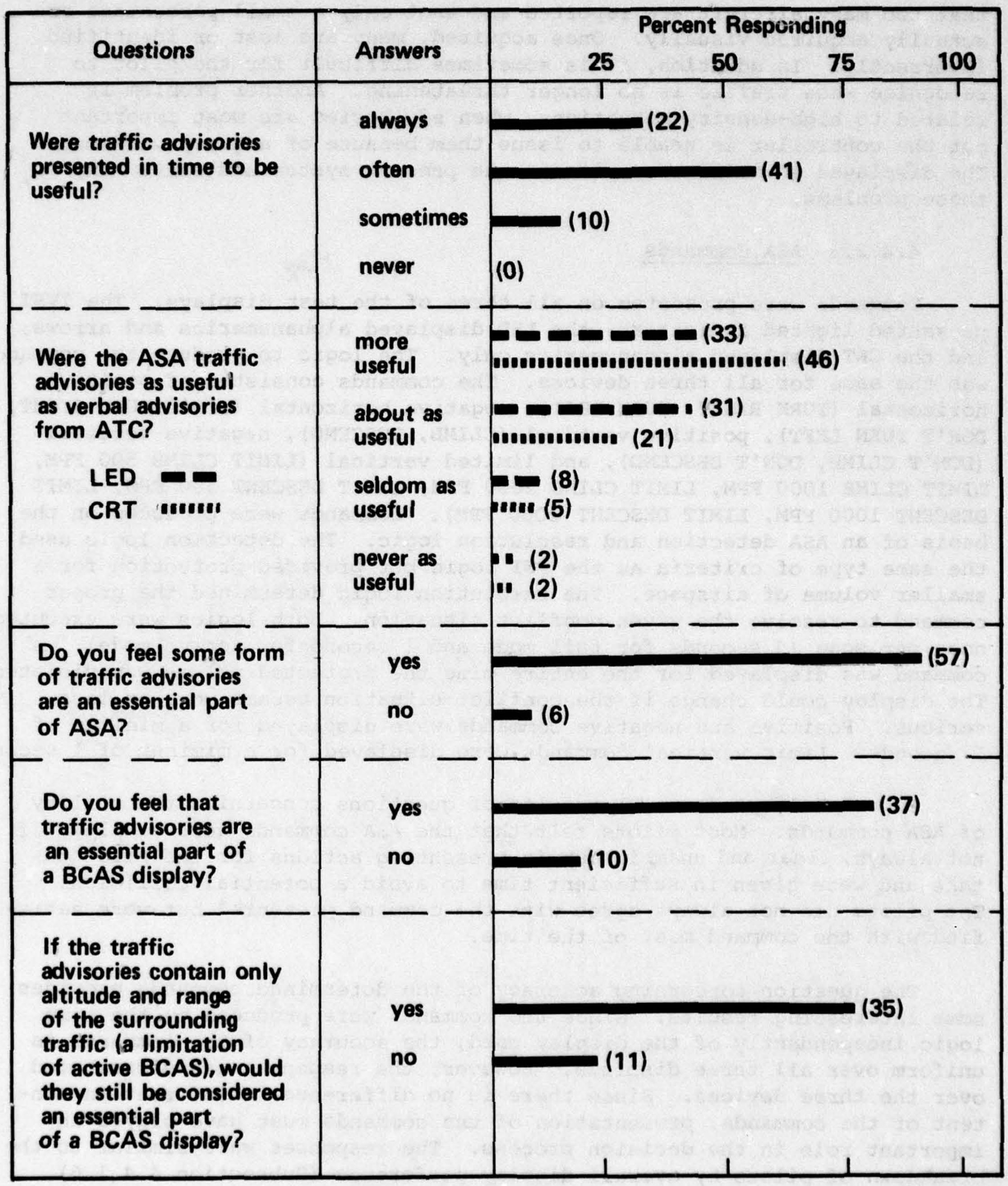


Figure 4-14. TRAFFIC ADVISORIES (UTILITY)

that too many aircraft are reported and that only a small percentage are actually acquired visually. Once acquired, many are lost or identified incorrectly. In addition, it is sometimes difficult for the pilot to recognize when traffic is no longer threatening. Another problem is related to high-density situations, when advisories are most important but the controller is unable to issue them because of a heavy workload. The displayed advisories complement the present system and solve many of these problems.

4.4.2.3 ASA Commands

Commands were presented on all three of the test displays. The IVSI presented lighted indicators; the LED displayed alphanumerics and arrows; and the CRT displayed alphanumerics only. The logic to produce the commands was the same for all three devices. The commands consisted of positive horizontal (TURN RIGHT, TURN LEFT), negative horizontal (DON'T TURN RIGHT, DON'T TURN LEFT), positive vertical (CLIMB, DESCEND), negative vertical (DON'T CLIMB, DON'T DESCEND), and limited vertical (LIMIT CLIMB 500 FPM, LIMIT CLIMB 1000 FPM, LIMIT CLIMB 2000 FPM, LIMIT DESCENT 500 FPM, LIMIT DESCENT 1000 FPM, LIMIT DESCENT 2000 FPM). Commands were produced on the basis of an ASA detection and resolution logic. The detection logic used the same type of criteria as the PWI logic but provided protection for a smaller volume of airspace. The resolution logic determined the proper command to resolve the given conflict situation. Both logics were executed once per scan (4 seconds for full mode and 1 second for active mode). A command was displayed for the entire time the protected volume was violated. The display could change if the conflict situation became more or less serious. Positive and negative commands were displayed for a minimum of 5 seconds. Limit vertical commands were displayed for a miminum of 1 second.

Figure 4-15 presents the results of questions concerning the utility of ASA commands. Most pilots felt that the ASA commands were usually, if not always, clear and unambiguous in presenting actions for the pilot to take and were given in sufficient time to avoid a potential collision. The pilots did not always agree with the command presented but were satisfied with the command most of the time.

The question concerning accuracy of the determined commands provides some interesting results. Since the commands were produced by the same logic independently of the display used, the accuracy of the commands is uniform over all three displays. However, the responses are distributed over the three devices. Since there is no difference in information content of the commands, presentation of the commands must have played an important role in the decision process. The responses were similar to the breakdown of pilots by overall display preference (Subsection 4.4.1.6). Those who favored the IVSI overall felt that it was most accurate as well. There are some differences in the LED and CRT responses, however. The LED display scored higher in accuracy than in overall preference, with the CRT display making up the difference. This may indicate that the LED presentation of commands (arrows and text) may be the preferred presentation and therefore may appear more accurate.

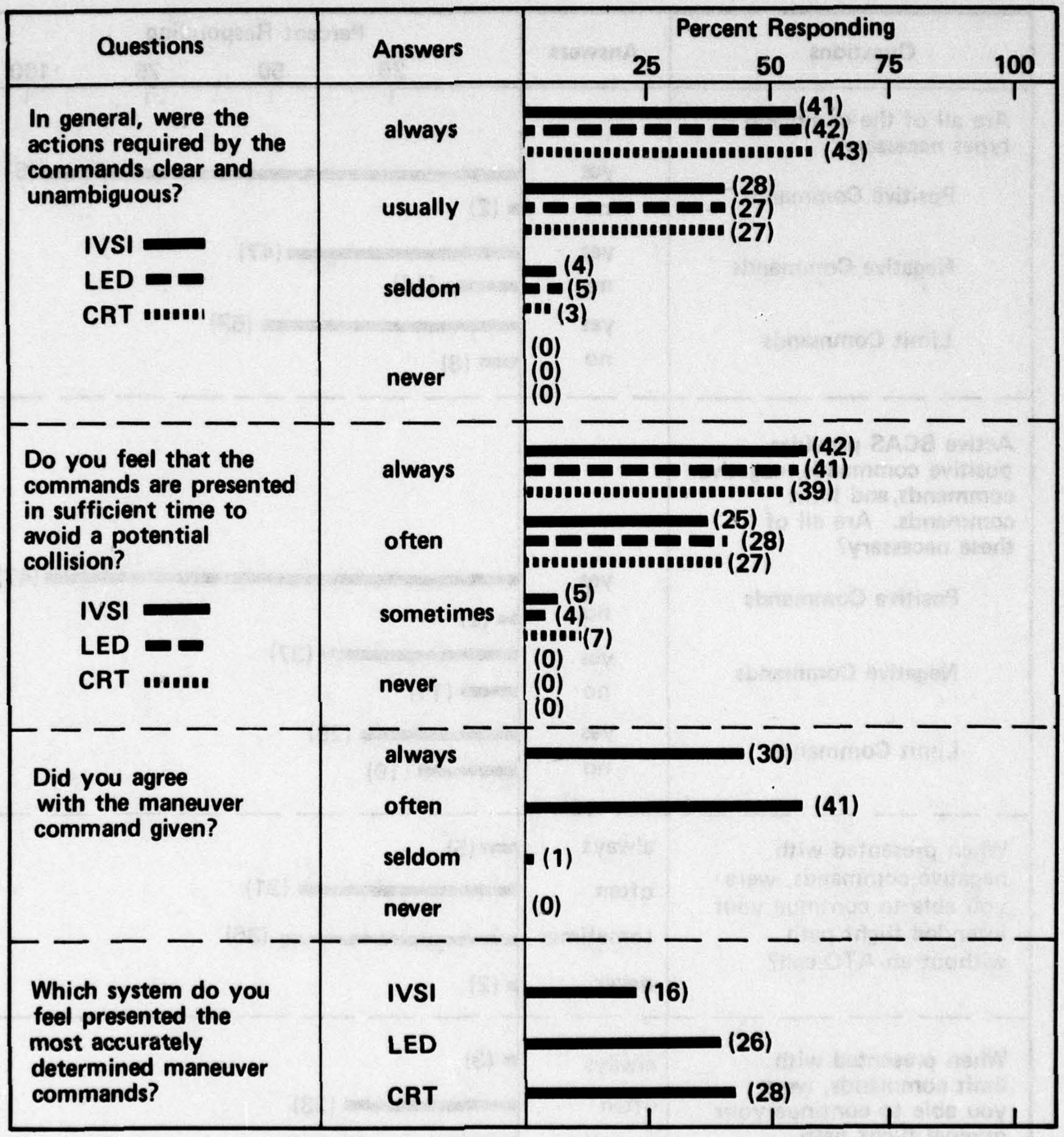


Figure 4-15. COMMANDS (UTILITY)

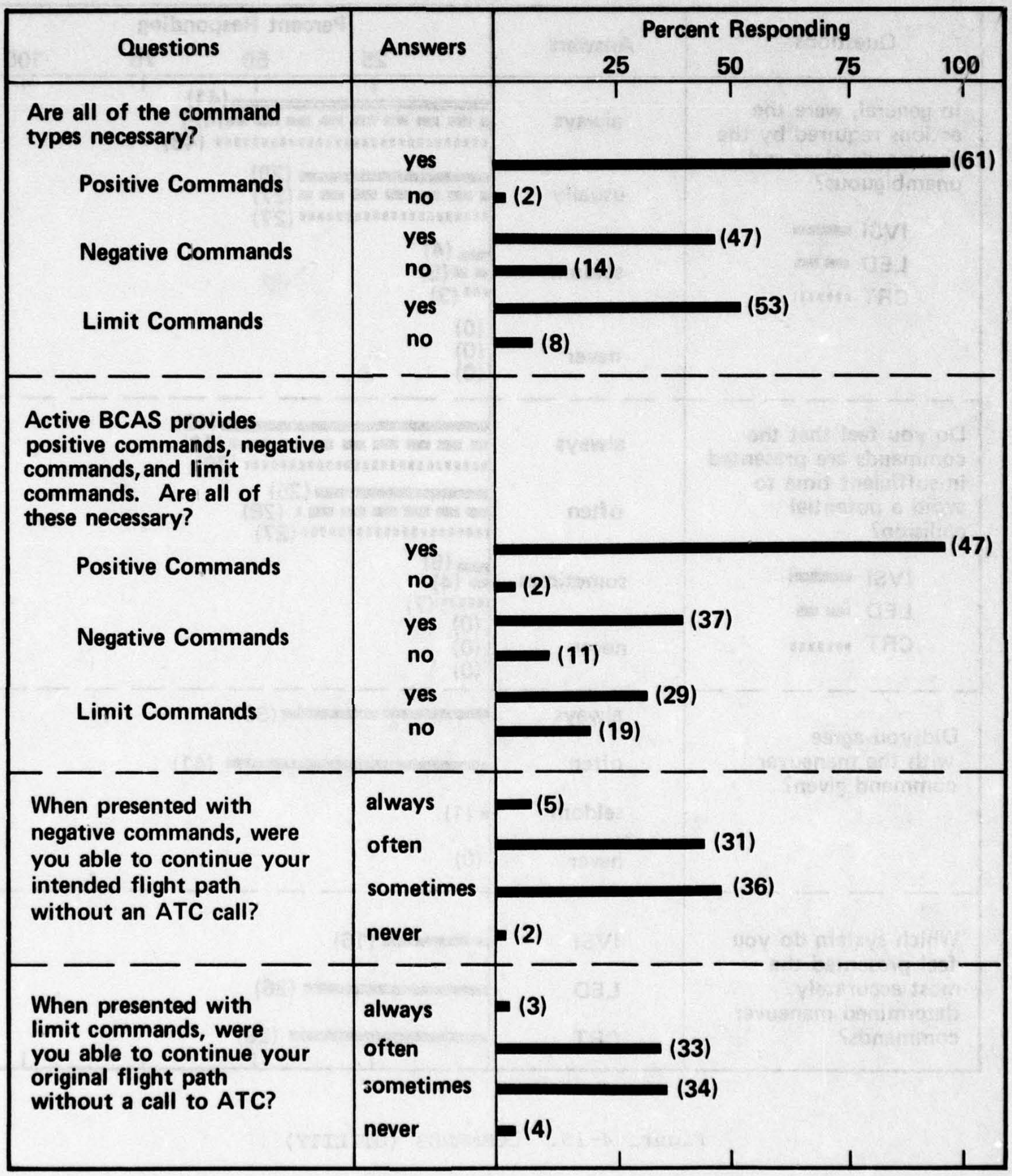


Figure 4-15. (continued)

Two questions on the necessity of the three command types (positive, negative, and limit commands) were presented -- one in the debriefing questionnaire and one in the supplemental questionnaire. The purpose of the second question was to determine if the pilots had changed opinions, given time to think about the experiment. The original responses indicated a favorable reaction to all of the command types. However, the supplemental question indicates a change of opinion with regard to limit commands. The favorable response dropped from 86 percent of the respondents (36 pilots) to 62 percent of the respondents (26 pilots) for the same sample of 42 responding pilots. Questions on the other two command types (positive and negative) received the same responses as the original question.

The last two questions concerned negative and limit commands and tried to determine if the subject pilots were able to continue their original flight path without a call to ATC. The consensus for both command types is that most pilots could manage without ATC calls in some circumstances, and almost half the pilots could often avoid the call.

4.4.3 Impact of Introducing Aircraft Separation Assurance on Flight and ATC Procedures

This section examines the issues of pilot workload, system-generated maneuvers, false alarms, pilot confidence in the system, ASA usefulness, and impact on ATC.

The introduction of any new system into the flight deck has some impact on crew workload. Pilots were queried specifically on this subject; the results appear in Figure 4-16. Most pilots felt that at worst the introduction of ASA would be an acceptable increase in workload and that of the three displays, the IVSI would be least unacceptable.

Communications probably was a factor in those results. Figure 4-17 shows that more than half of the pilots surveyed felt that ASA would require more communication with ATC. The greatest concern among pilots is causing secondary collisions when deviating from an ATC clearance as a result of an ASA command. Therefore, pilots feel that any deviations from their assigned clearance must be reported to ATC. Furthermore, many pilots expect that they will contact ATC regarding traffic advisories of aircraft that are close but not visually acquired. On the other hand, there are some pilots who feel that ATC will need to give fewer traffic advisories, which will reduce the communications load. Nevertheless, most pilots felt that the ATC controller should be kept aware of any commands given by ASA in the form of either voice or data link communication.

The effect of ASA-generated command maneuvers is investigated in Figure 4-18. The results show that there was seldom a strong preference for vertical commands, but there was a preference for horizontal commands during takeoff, approach, and landing. Those pilots who preferred horizontal maneuvers offered the following justifications:

> There is less probability of a secondary encounter following a horizontal maneuver.

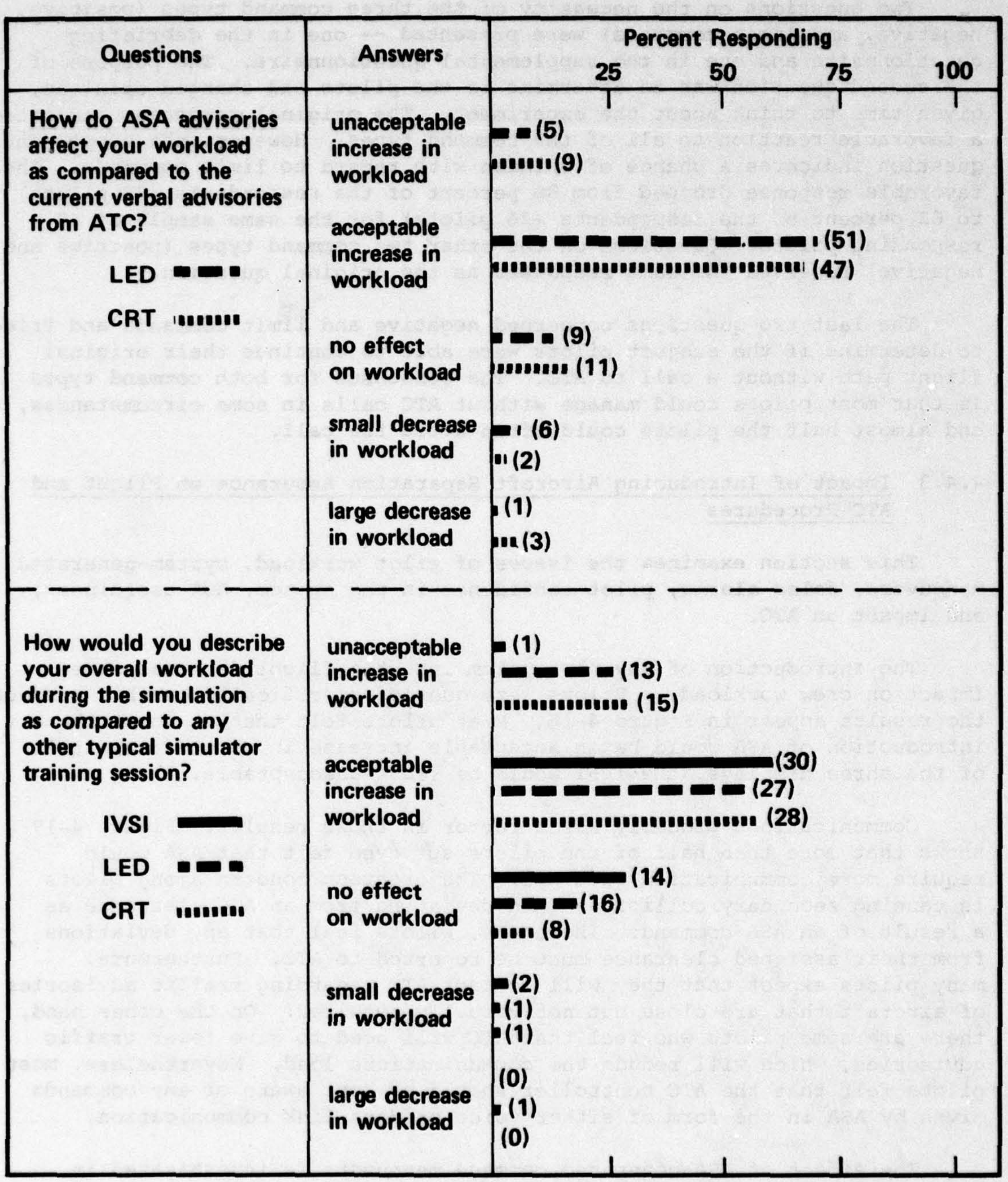


Figure 4-16. PILOT WORKLOAD

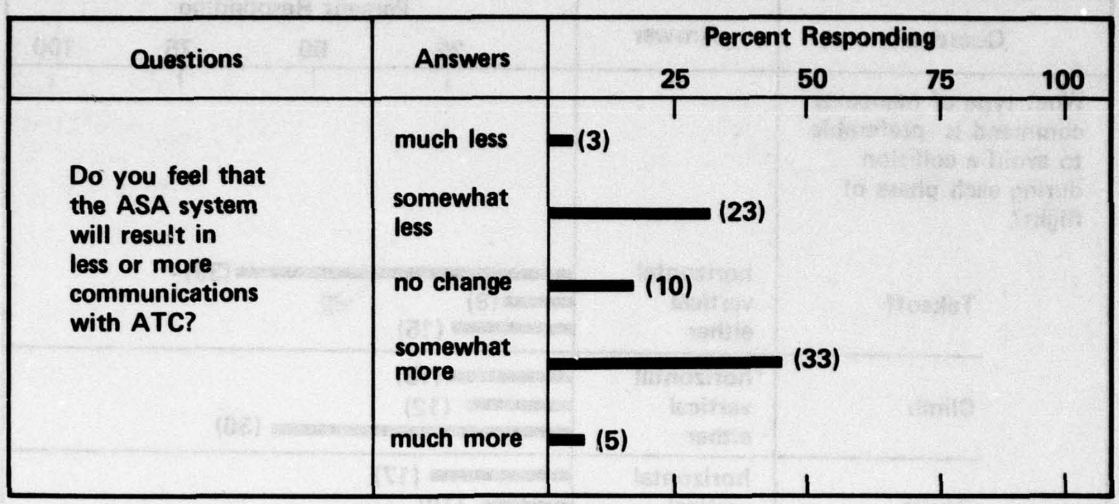


Figure 4-17. COMMUNICATIONS WORKLOAD

- The idea of not "busting" altitude is ingrained in each pilot's thinking from the start of his training.
- A positive G load provides for passenger comfort, passenger safety (meal service, passengers in aisles, etc.), and less passenger anxiety (passengers are often unaware of horizontal maneuvers).
- There is more concern about terrain problems with a vertical as opposed to a horizontal maneuver.
- With gear and flaps down, many aircraft cannot climb.
- No power changes are necessary.

The pilots who preferred vertical maneuvers had these comments:

- Vertical maneuvers provide a more rapid flight-path change (at most speeds) than horizontal.
- Vertical commands are easier to respond to.
- There is generally more vertical airspace available for maneuvering.

Regardless of the maneuver type, there was considerable concern among the pilots about maneuvering into another aircraft. This is borne out in specific results that show a majority at least sometimes concerned. While there was a substantial difference between the displays, the IVSI caused the most concern, and the CRT caused the least.

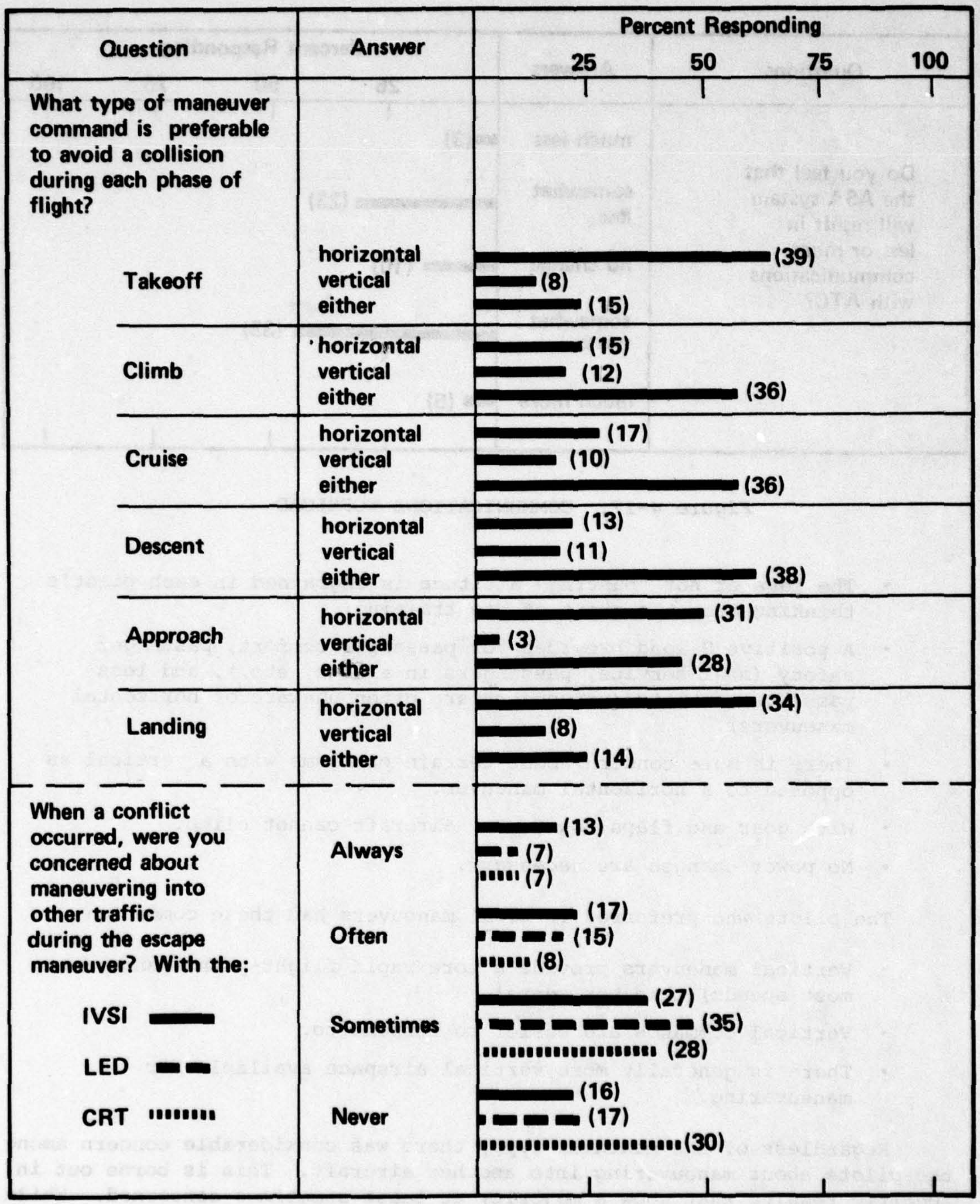


Figure 4-18. SYSTEM-GENERATED MANEUVERS

Magnitude of the pilot response to the ASA commands is examined in Figure 4-19. It should be noted that these results reflect the pilots' own perception of their maneuvers. Pilots sometimes perceived larger than normal vertical maneuvers but seldom perceived larger than normal horizontal maneuvers.

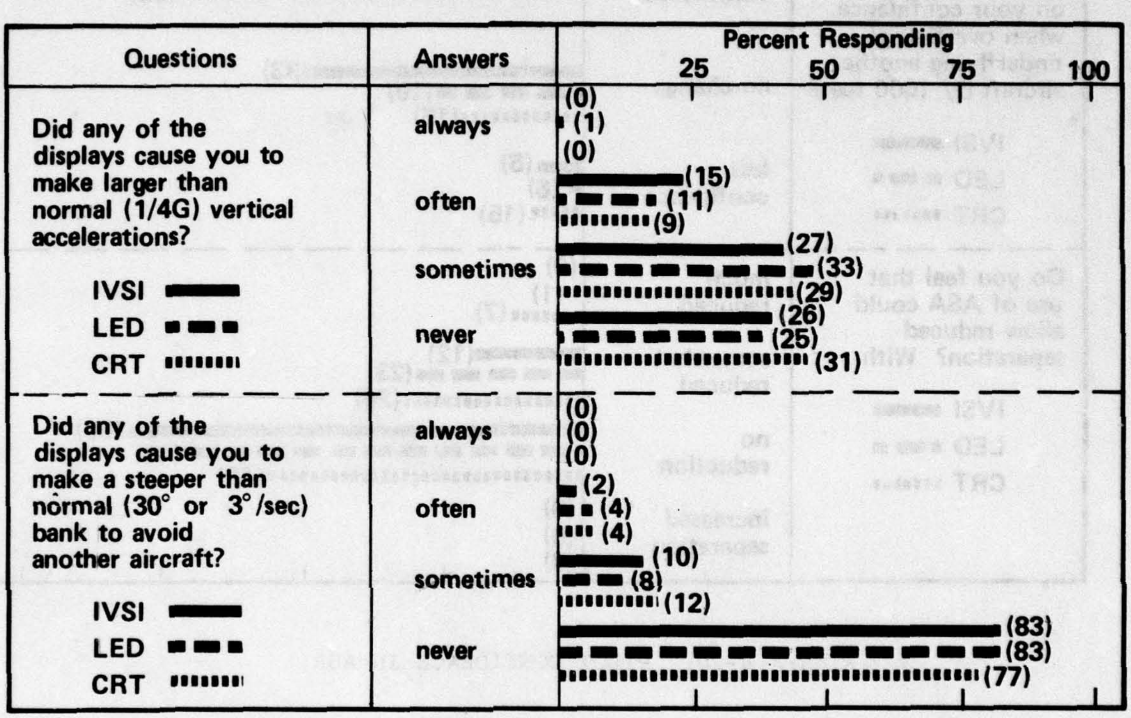


Figure 4-19. MAGNITUDE OF PILOT RESPONSE

Confidence issues are investigated in Figure 4-20. Pilots expressed increased confidence under ASA when overflying or underflying aircraft by 1,000 feet, with a higher degree of confidence associated with the LED and CRT displays. However, this increased confidence was not enough to encourage reduced lateral separation. Again, more confidence was placed in the LED and CRT displays.

Another confidence issue concerns unnecessary alarms -- those alarms caused by situations that would normally be resolved by the planned action of either or both aircraft. This type of situation was presented on occasion during the simulation and was observed by the pilots as illustrated in Figure 4-21. Pilots' comments on this situation indicate that if the pilot knows why the system alarmed because of available supporting information (such as intruder position information), then these "unnecessary" alerts will reinforce rather than destroy confidence in the system. However, the lack of supporting information will be detrimental to crew acceptance. It was also stated that ASA must work every time because pilots and controllers

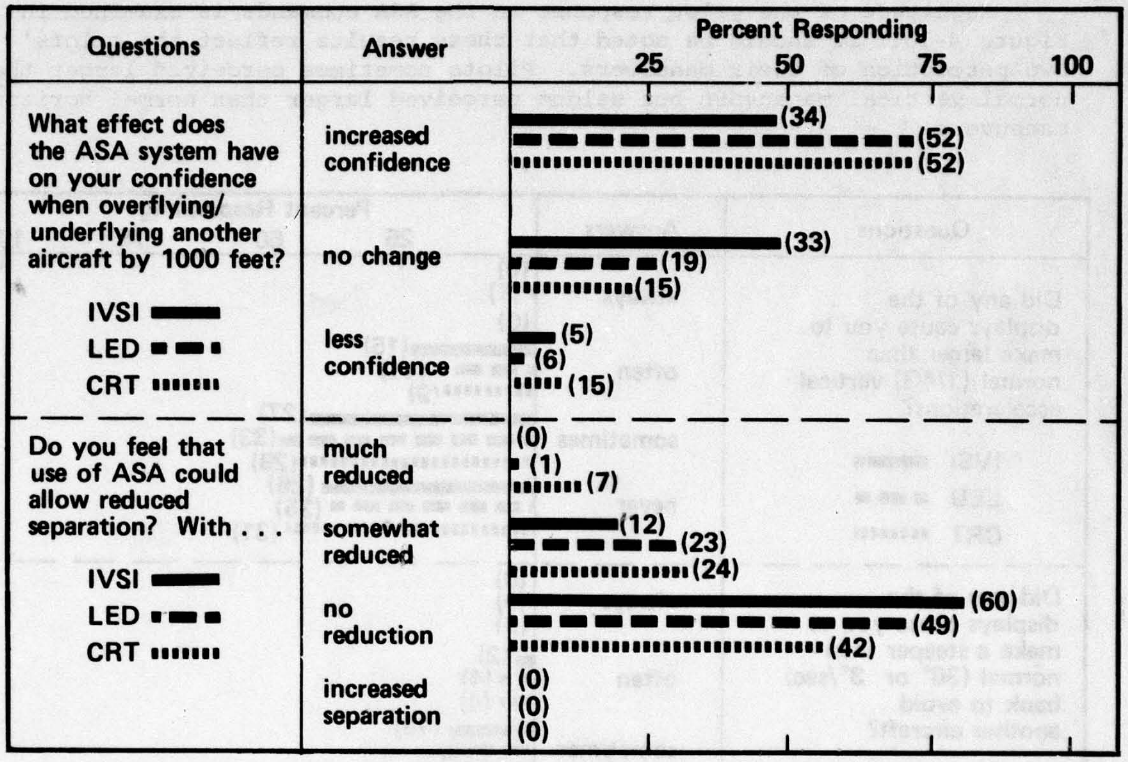


Figure 4-20. PILOT CONFIDENCE IN ASA

would tend to rely on the system very heavily. On the other hand, if the system proves unreliable, pilots will mentally "tune out" the display and ignore the ASA commands.

When asked about the changes that would be required in aircraft operating procedures if ASA were implemented, most pilots felt that none were required. Those who commented saw added duties for the nonflying pilots (monitoring of the ASA display), a requirement to equip all aircraft with transponders, and changes in the nominal instrument scan.

Comments on changes to ATC operations, however, included the entire spectrum of changes -- from no changes to revamping terminal ATC. Typical pilot comments are as follows:

- A provision required for immediately alerting ATC of a deviation from a cleared flight path
- Fewer aircraft under each sector controller
- Fewer required traffic advisories
- More traffic advisories required to prevent unnecessary maneuvering

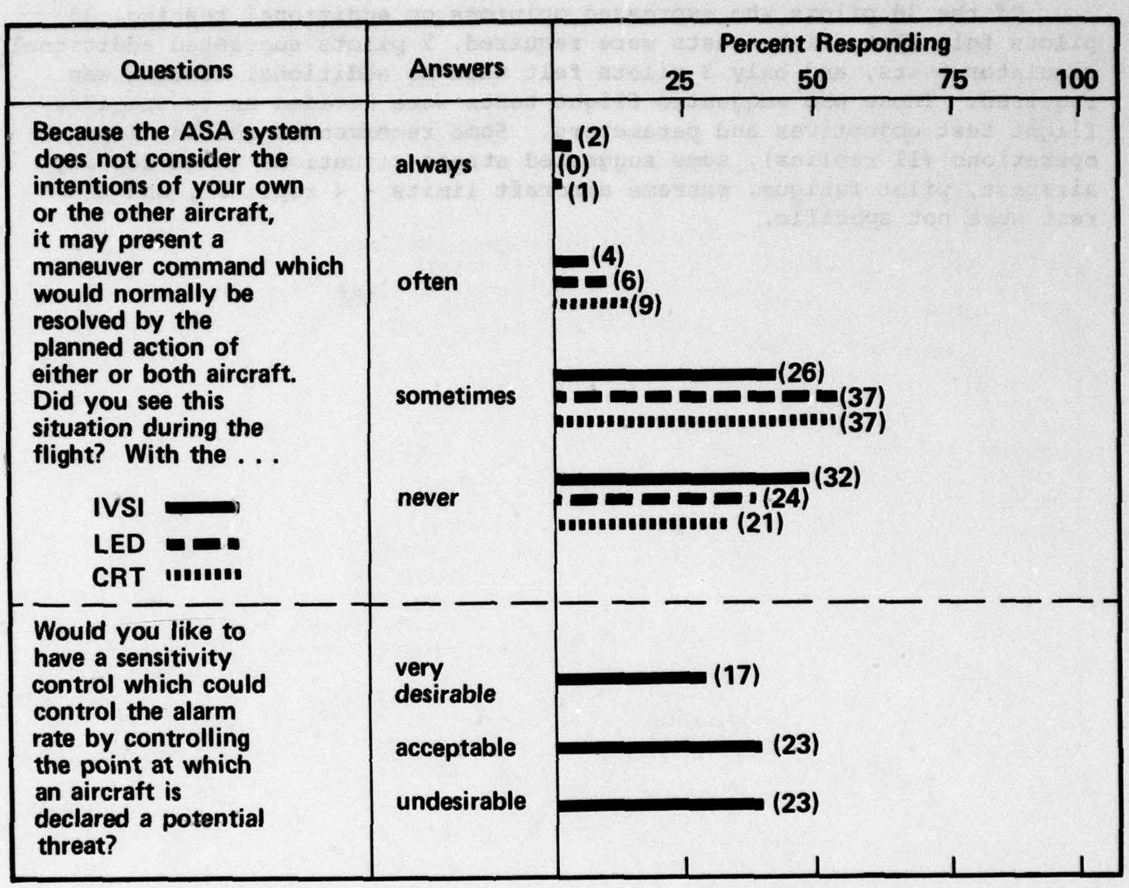


Figure 4-21. UNNECESSARY ALARMS

- Increased separation in terminal areas due to unanticipated aircraft deviations
- Reduced separation in some areas
- Removal of the 250-knot speed limit below 10,000 feet -- increased traffic flow
- No changes required

More than 80 percent of the pilots answered the question, "Do you feel that the ASA system as used in this simulation will result in safer operation in respect to midair collision?" with an unqualified yes, and comments such as "We've needed it for years" and "Yesterday wasn't soon enough" were offered; however, most pilots felt that additional testing would be required before implementing ASA.

Of the 38 pilots who expressed opinions on additional testing, 33 pilots felt that flight tests were required, 2 pilots suggested additional simulator tests, and only 3 pilots felt that no additional testing was required. Those who suggested flight tests were divided as to specific flight test objectives and parameters. Some recommended routine line operations (11 replies), some suggested stress situations (high-density airspace, pilot fatigue, extreme aircraft limits - 4 replies), and the rest were not specific.

CHAPTER FIVE

QUANTITATIVE DATA ANALYSIS

The quantitative data analysis consists of an evaluation of pilot performance and command effectiveness. Pilot performance was measured in terms of pilot response (time and magnitude) to displayed collision avoidance commands, and command effectiveness was evaluated by examining resultant miss distances.

Since pilot response time is one of the key factors in determining look-ahead times for the collision avoidance detection logic, the analysis will give some indication of the adequacy of the assumed average response time. Response time can also be used to provide some information on display efficiency. If it can be assumed that crews did not respond until they comprehended the conflict situation and interpreted the displayed information, significantly different response times for the three displays could reflect the efficiency of those displays or the information presented on them.

Magnitude and rate of response were also measured as indicators of pilot performance. Pilots were briefed before the simulation sessions that sufficient warning would be presented by the collision avoidance system to escape a conflict situation by performing standard-rate horizontal and vertical maneuvers. Deviations from the norm could indicate workload problems or apprehension with the conflict situation.

To determine command effectiveness, individual conflicts were examined to assess the cause of small miss distances and to permit developing recommendations regarding algorithmic or procedural changes.

5.1 DATA COLLECTION

The quantitative data collected during this evaluation consist of a time-stamped record of events for each flight scenario. Data were recorded on cockpit simulator parameters (position, velocity, and attitude), command and intruder parameters, and simulation controller interaction.

5.1.1 Simulator Parameters

The simulator data consist of position (x, y, z), velocity ($\dot{x}$, $\dot{y}$, $\dot{z}$), and attitude data (pitch angular rate, roll angle, and yaw angle). Pitch

angular rate and roll angle data were updated each 1/20 of a second. All other data were collected at 1-second intervals. Position and velocity data are referenced to a runway-oriented coordinate system centered at the takeoff point of the Los Angeles International Airport runway 24R, with the Y-axis along the runway centerline (magnetic heading 248°) and the X-axis offset 90° in a clockwise direction. Twenty successive pitch angular rate and roll angle data samples were accumulated in arrays and recorded, together with the remainder of the simulator data, at 1-second intervals. Each record was time-stamped, with the time being expressed in seconds following the initiation of simulation.

5.1.2 Command and Intruder Data

At each occurrence of a new command, the command (coded in a simple format) was recorded, together with an index into the track file of the aircraft causing the command and the time at which the new command was initiated relative to simulation initiation. Miss distance information was updated continuously and written to disk when the display was cleared. The record included the point of closest approach (range and altitude), the time at which the point was reached, and the time at which the display was cleared.

While it was a simulation controller input that released an intruder aircraft into the simulation, the track was not initiated until the simulator was a fixed distance from a fixed reference point. At that time, a time-stamped record was written to disk; it included track ID, initial position, initial heading, and initial speed.

5.1.3 Simulation Controller Interaction

The simulation controller had the ability to request information about simulation activities and make modifications to the simulation to control those activities. Since these modifications were unique to each simulation session, a time-stamped record was written to disk at each occurrence. The simulation controller inputs are as follows:

1. Change Mode. ASA mode changed from full to active and back again
2. Kill Aircraft. Eliminate an aircraft from the simulation (track ID dumped)
3. Altitude-Speed Change. Modify the flight plan of the intruder aircraft to ensure a collision (track ID and magnitude of altitude/speed change)

5.2 RESPONSE-TIME ANALYSIS

Pilot response time is defined as the time elapsed from command presentation to maneuver initiation. Maneuver initiation is defined as a 1-degree change in roll angle (horizontal maneuvers) or a 1/2-degree-per-second change in pitch rate (vertical maneuvers). These values were

selected empirically by examining the data and observing how maneuvers evolved from steady-state conditions.

The response times were generated for each command and were labeled according to its associated display type (IVSI, LED, or CRT), ASA mode (active or full), scenario (1 to 6), and command type (CLIMB, DESCEND, DON'T CLIMB, DON'T DESCEND, LIMIT CLIMB 500, 1,000, or 2,000 feet per minute, LIMIT DESCENT 500, 100, or 2,000 feet per minute, TURN RIGHT, TURN LEFT, DON'T TURN RIGHT, AND DON'T TURN LEFT). The response times were recorded to 1-second accuracy. However, the averages are presented to three decimal digits to permit better comparisons between them. Since less than 1 percent of all response times exceeded 10 seconds (6 out of 656 response times), all such "outliers" were eliminated from the data sets. In addition, five of six large response times were associated with negative or limit commands. Since these commands may not have required any action from the pilot, the large response times may have been a result of normal flight path changes.

Frequency distributions of response times were created for each of the factors of interest in the evaluation -- display type, ASA mode, scenario, and command type. An examination of response times disclosed that the data were not normally distributed. A gamma distribution yielded a goodness-of-fit of 0.922, which was not considered especially conclusive. Curve-fitting with other common distributions was similiarly inconclusive; distribution-free (nonparametric) methods were therefore used to correlate response times to the various influencing factors.

To simplify comparisons of the distributions, the frequency data were converted into probability of occurrence, which is defined as the number of occurrences for each time interval divided by the number of occurrences for all time intervals. The Kolmogorov-Smirnov test was used as a comparison test between distributions. The test examines the difference between two distributions and determines whether the differences are due to chance or the distributions are significantly different. For multiple comparisons involving several distributions, a rank test analogous to the classical Analysis of Variance (ANOVA) method was employed. This permits the simultaneous study of the effects of several factors. The Kruskal-Wallis One-Way Analysis of Variance was used to test the null hypothesis that there was no significant difference among the expected values of several populations. Observed differences in samples were tested to determine whether they were true differences or random variations resulting from "noise" in the data. The distribution-free method applied uses numbers that correspond to the relative ranking of data rather than the data themselves. A more detailed description of these tests is presented in Appendix F.

For each statistical test, an initial hypothesis about the nature of the responses is proposed, together with an alternate hypothesis. The objective of the test is to determine whether to accept or reject the original hypothesis in favor of the alternate hypothesis. The level of significance is the probability of rejecting the original hypothesis in favor of the alternate when the original hypothesis is actually true. The

tests in this analysis were conducted at the five percent level of significance to minimize the chance of drawing an incorrect conclusion from the data.

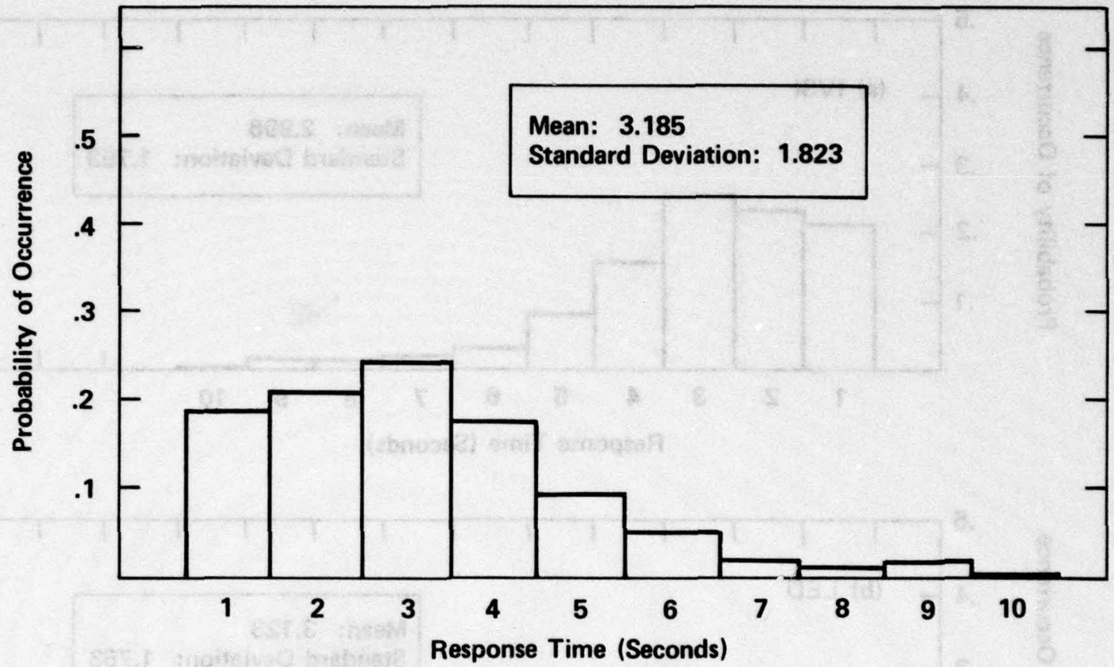
The probability distributions for measured response times appear in Figures 5-1 through 5-5. Figure 5-1 presents the probability distribution for the total population of measured response times. The mean for overall response time is 3.185 seconds, with a standard deviation of 1.823 seconds. The response times observed in this simulation appear to be consistent with previous studies that involved air transport aircraft.* These studies assumed a 1.5-second pilot response and 1-second servo delay, or 2.5-second total response time. The observed response times are significantly less than the 6-second values observed in some NAFEC studies.** However, there were some differences in the experimental approach. The NAFEC simulation used one-man general aviation crews in a GAT II trainer. This study used two- and three-man crews of professional airline pilots in a B-727 simulator. Further, in the NAFEC test an audible alarm sounded for positive commands only, while in this test series it sounded for all commands.

Since many of the conflict situations resulted in more than one command, the impact of subsequent commands on response time was also investigated. Figure 5-1 shows the response times for the first command in a command sequence. The resultant mean is 3.274 seconds, with a standard deviation of 1.652 seconds. The increase, when compared with the total population's average response times, is probably due to the pilot's awareness of a conflict situation at the time of the subsequent commands and the additional attention given to the collision avoidance display.

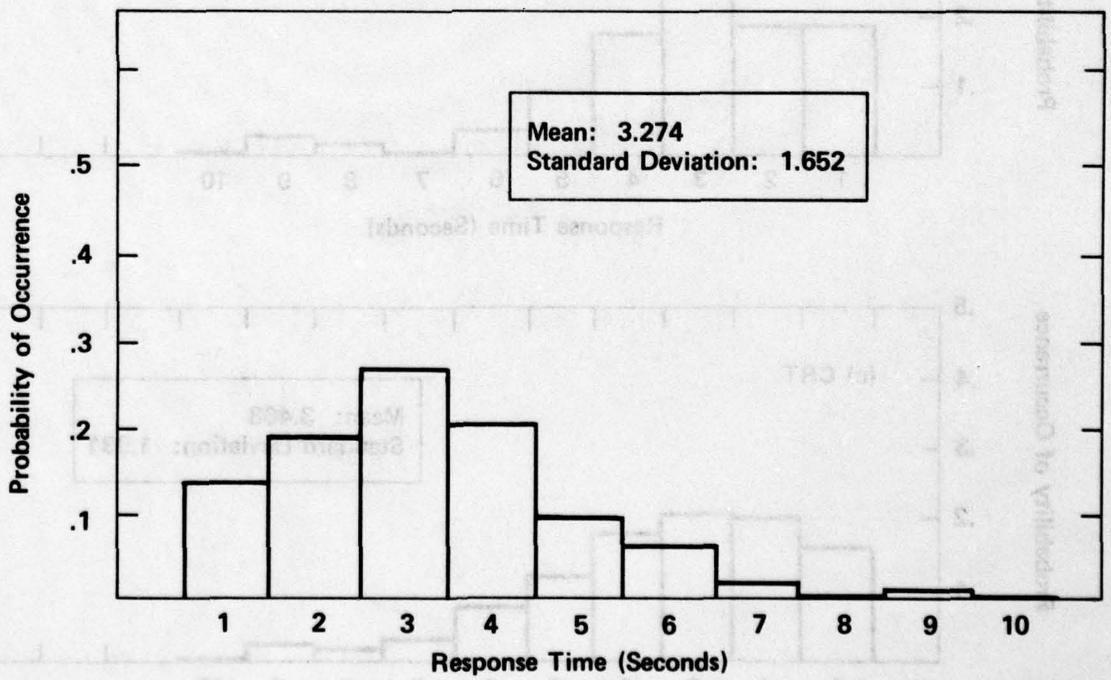
The data were broken down by display type (IVSI, LED, and CRT) and analyzed by using the Kurskal-Wallis methods for multiple comparisons. Figure 5-2 illustrates this breakdown by display type for the total population of response times. The results show a statistically significant difference, with the IVSI demonstrating the shortest response time (2.996 seconds); the LED was second (3.123 seconds), and the CRT produced the longest overall response time (3.468 seconds). However, these differences do not appear to have any operational significance. The differences could reflect the complexity of the display, its location with respect to the normal instrument scan, or some combination of the two factors. The IVSI was the simplest display to understand and was located in the normal instrument scan. The CRT was the most complex display to understand and was located outside the normal instrument scan.

**Evaluation of Threat Logic for the ATA ACAS*, Watson, Lazzareschi, Wedlake, Report No. MDC E0116, 13 March 1970.
"Analysis of Warning Times for Collision Avoidance Systems", John M. Holt, Ronald M. Anderson, *IEEE Transactions on Aerospace and Electronic Systems*, March 1968.

***Modeling Pilot Response Delays to BCAS Commands*, Report No. FAA-RD-79-74, October 1979.



(a) Total Population of Response Time



(b) First Command in Sequence Only

Figure 5-1. PROBABILITY DISTRIBUTIONS, ALL RESPONSE TIMES

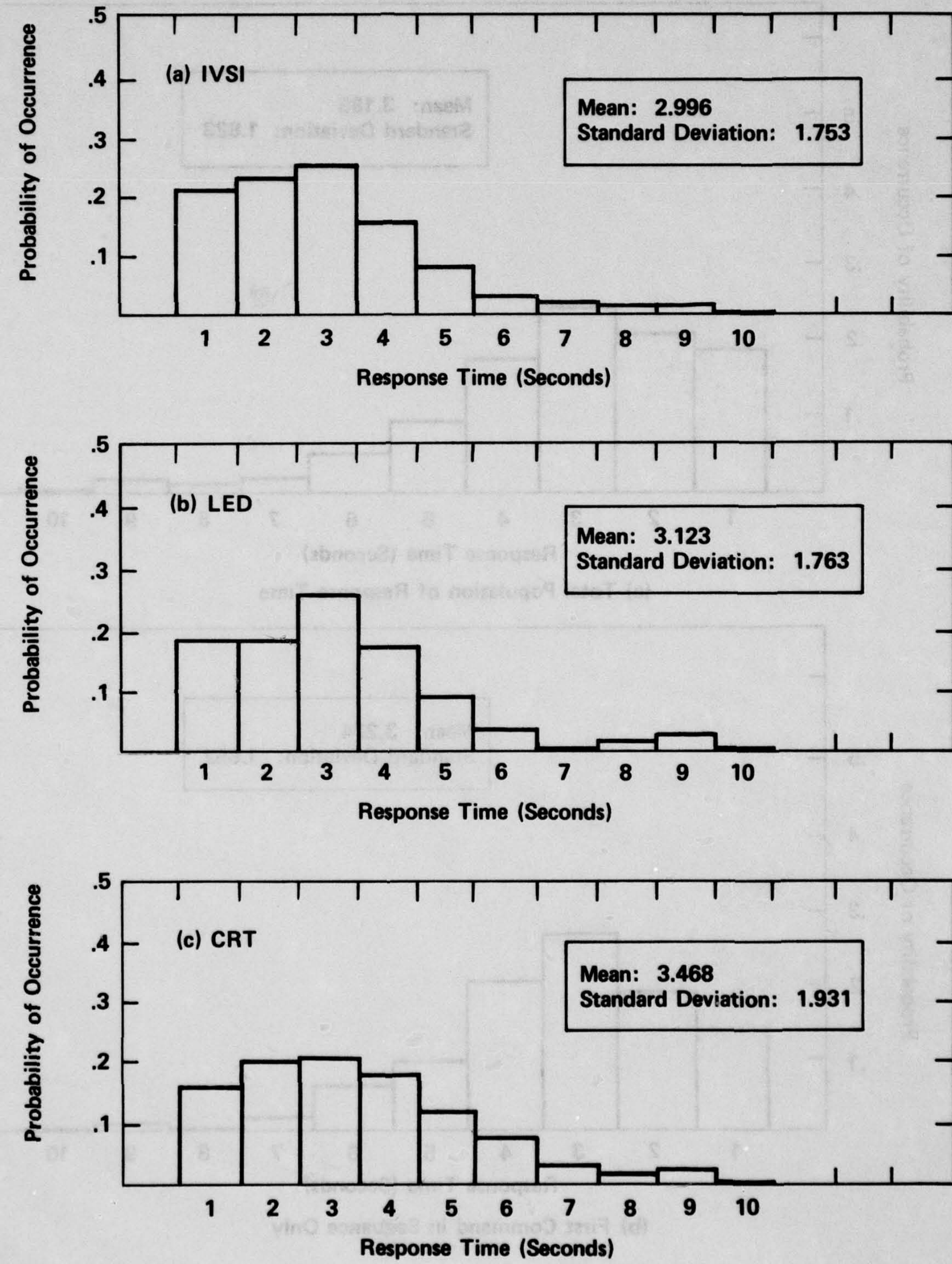


Figure 5-2. PROBABILITY DISTRIBUTIONS, TOTAL POPULATION BY DISPLAY TYPE

The impact of subsequent commands in a command sequence by display type was also investigated. The probability distributions are presented in Figure 5-3, and the entire breakdown of response time by display type is summarized in Table 5-1. With the exception of the IVSI, initial commands produced a longer response time, and subsequent commands were, on the average, 1/2 second shorter. The response times for the IVSI were statistically the same, indicating again that the positioning of the instrument in the normal scan may be significant.

The Kruskal-Wallis comparison test was also applied to response time data across scenarios for the first command in a sequence. The results of the test showed that, as expected, there are no statistically significant differences between response times over the six scenarios. The probability distributions of these response times appear in Figure 5-4.

The effect of ASA mode (full versus active) on response times was analyzed by using the Kolmogorov-Smirnov comparison test. The data used were those of the first command in a sequence. The results indicate that there are significant differences in response between the two modes of operation, with full mode requiring, on the average, 0.4 second longer. Since full mode includes both horizontal and vertical commands and active mode includes vertical commands only, the effect of horizontal versus vertical commands was investigated. A second comparison was performed between full mode (vertical commands only) and active mode (all commands). The results show no significant difference in response times, indicating that horizontal maneuvers increase pilot response time. The results are summarized in Table 5-2, and the frequency distributions appear in Figure 5-5.

The last influencing factor investigated was the command type. Again, the first command in the sequence was representative of the actual response time.

The first test performed compared pairs of commands that were of the same type but opposite in direction (e.g., CLIMB versus DESCEND, TURN RIGHT versus TURN LEFT, DON'T CLIMB versus DON'T DESCEND, etc.). There were no significant differences in any of the pairs tested.

The second test compared the four pairs of positive and negative commands (the sample size was too small to compare limit commands). Negative commands were considered only if an action was taken by the pilot. Analysis of variance indicated that horizontal commands require more time than vertical commands. This is verified by visual inspection of the averages summarized in Table 5-3.

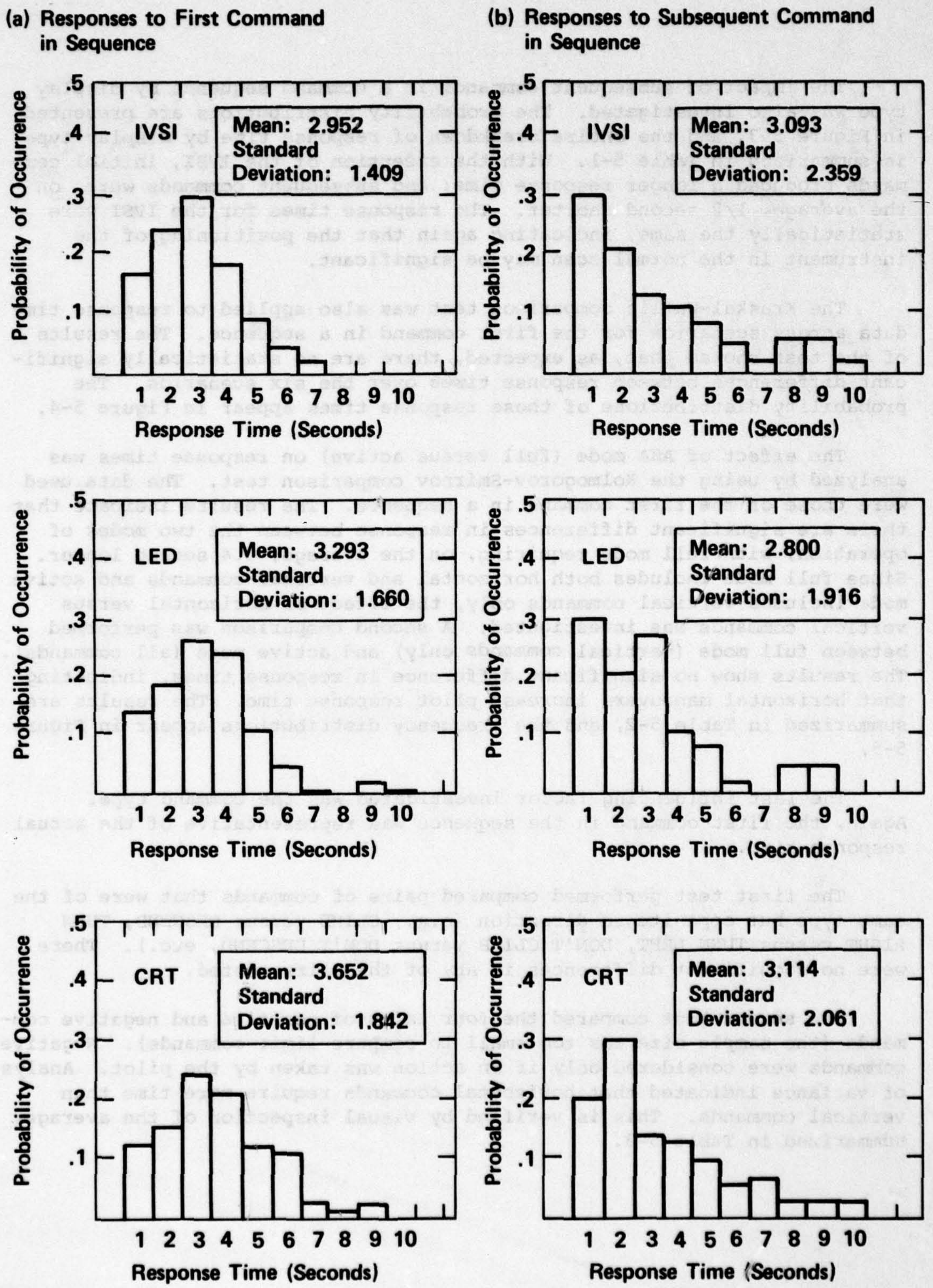


Figure 5-3. PROBABILITY DISTRIBUTIONS, FIRST COMMAND/SUBSEQUENT COMMAND BY DISPLAY TYPE

Table 5-1. MEAN RESPONSE TIME SUMMARY BY DISPLAY

Display	Response Time to All Commands			Response Time to First Command in a Sequence			Response Time to Subsequent Commands in a Sequence		
	Number Samples	Mean	Standard Deviation	Number Samples	Mean	Standard Deviation	Number Samples	Mean	Standard Deviation
IVSI	242	2.996	1.753	167	2.952	1.409	75	3.093	2.359
LED	203	3.123	1.763	133	3.293	1.660	70	2.800	1.916
CRT	205	3.468	1.931	135	3.652	1.842	70	3.114	2.061

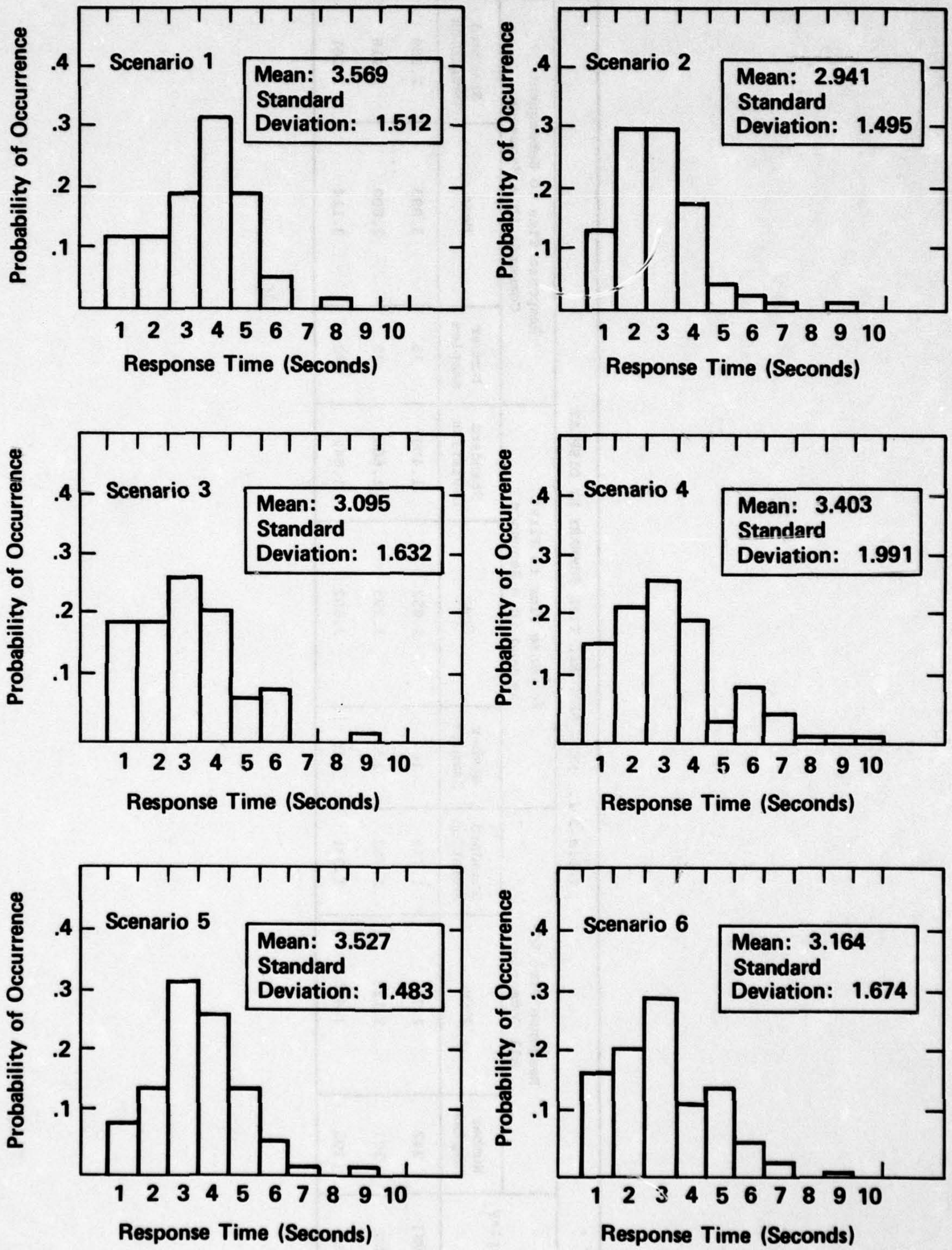


Figure 5-4. PROBABILITY DISTRIBUTIONS -- BY SCENARIO (RESPONSES TO FIRST COMMAND IN SEQUENCE)

Table 5-2. MEAN RESPONSE TIME SUMMARY BY MODE			
Mode	Response Time to First Command in a Sequence		
	Number Samples	Mean (Specifications)	Standard Deviation
Full (All Commands)	239	3.402	1.849
Full (Vertical Commands)	144	3.028	1.613
Active (All Commands)	196	3.092	1.722

5.3 MAGNITUDE OF RESPONSE

Subject pilots were advised before the simulator session of the following collision avoidance procedures:

- Initiate an escape maneuver if
  - A conflict is perceived in the cockpit visual system.
  - A conflict is perceived on the basis of displayed traffic advisory information.
  - A command is presented
- Respond to the command in the following maneuver:
  - Climb Maneuver. Rotate to a pitch-up attitude approximating a go-around configuration.
  - Descent Maneuver. Reduce thrust. Pitch over at an attitude approximating a profile descent.
  - Turn Maneuver. Roll into a 30° bank in the direction of the command.
  - Limit Vertical Command. Obey the limit instruction.
  - No Turn Command. Cease or avoid turning in the direction of the command.
- Terminate an escape maneuver if
  - The displayed command is cleared.
  - The conflict no longer exists and the display is clear.

Pilots were specifically instructed to perform normal maneuvers at standard rates to avoid a collision. Therefore, it can be assumed that rates in excess of nominal values indicate an apprehension about the system. There is great concern among airline pilots regarding passenger comfort and safety, and if maneuvers with excessive rates are an instinctive reaction to ASA, the system may ultimately prove to be unacceptable.

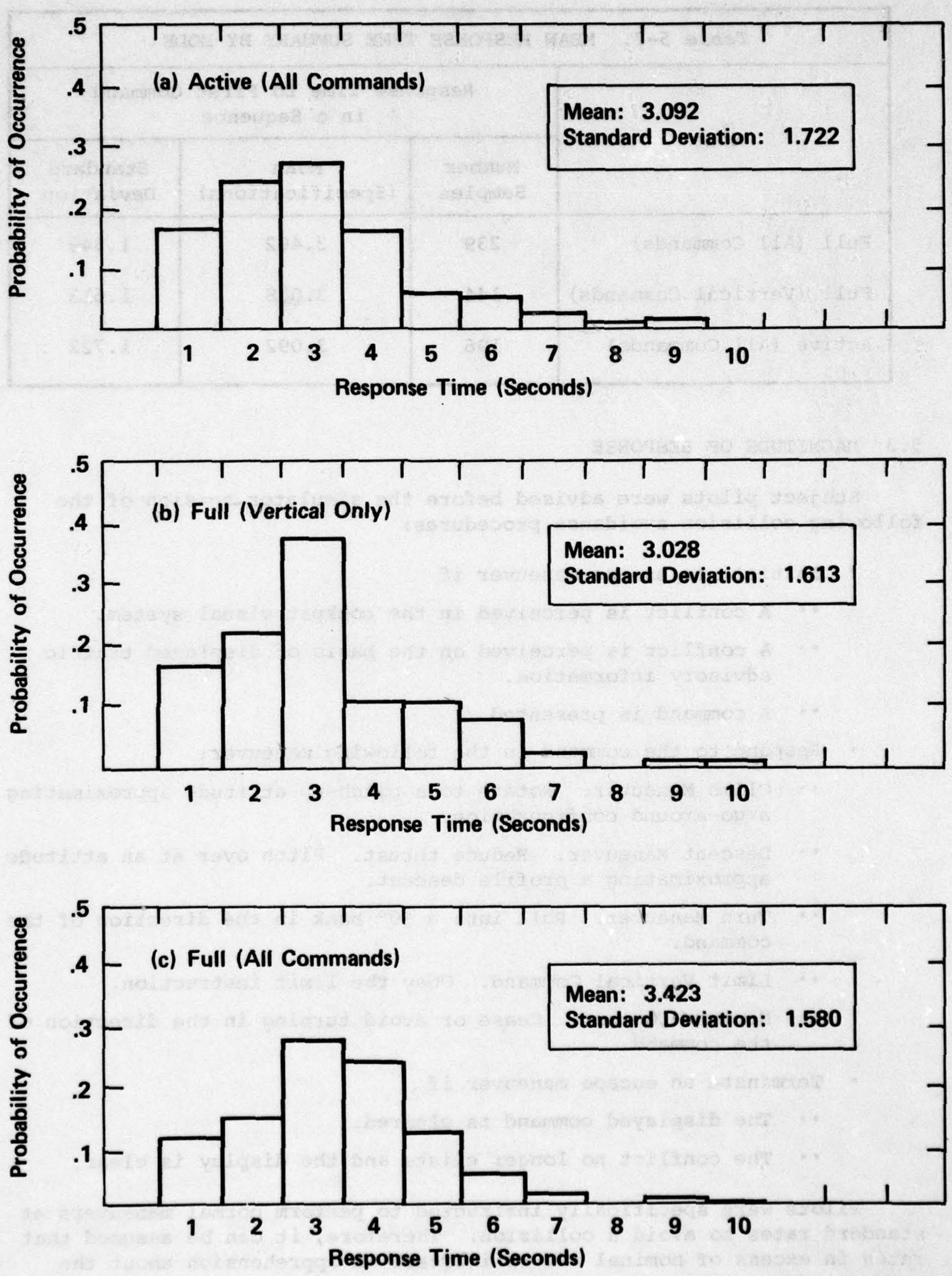


Figure 5-5. PROBABILITY DISTRIBUTIONS -- BY MODE (RESPONSES TO FIRST COMMAND IN SEQUENCE)

Table 5-3. MEAN RESPONSE TIME BY COMMAND		
Mode	Response Time to First Command in a Sequence	
	Mean	Standard Deviation
DESCEND	3.195	1.703
CLIMB	2.915	1.213
DON'T DESCEND	2.917	1.933
DON'T CLIMB	2.975	1.625
DON'T TURN RIGHT	4.391	1.877
DON'T TURN LEFT	4.000	1.414
TURN RIGHT	3.808	0.939
TURN LEFT	3.950	1.154

Magnitude of pilot response was measured in terms of roll angle and pitch rate. Maximum values achieved were determined for each positive command encountered. A frequency distribution of maximum roll angles is illustrated in Figure 5-6.

There were significantly more left turn commands than right turn commands because of the nature of the scenarios and conflict geometries used. A comparison test showed that there was no significant difference between the distributions of right and left turn maximum roll angles. The results are centered on a 30° bank for both right and left turns, as expected on the basis of the instructions that the pilots received before the simulator session. Some of the larger responses can be explained as follows:

- Slow response to first command in sequence (positive command was a follow-up)
- Simulator already in left bank
- Apprehension due to lack of visual acquisition

The last reason was the one given most often by the pilots for large maneuver rates. The rates were not held for very long, however. The large maximum roll angles were generally no more than 1 second in duration before the pilot began rolling out of the bank.

Maximum pitch rates were also analyzed. Figures 5-7 and 5-8 show the probability distributions for descend and climb commands for all commands and for the first command in a sequence. Comparison tests performed on the data detected no significant differences in the magnitude of vertical maneuvers between all commands and first command in a sequence. Differences

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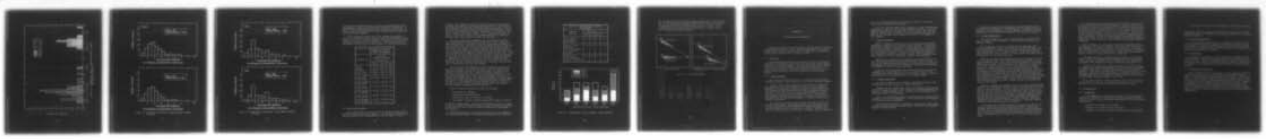

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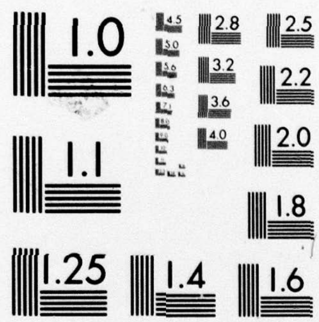

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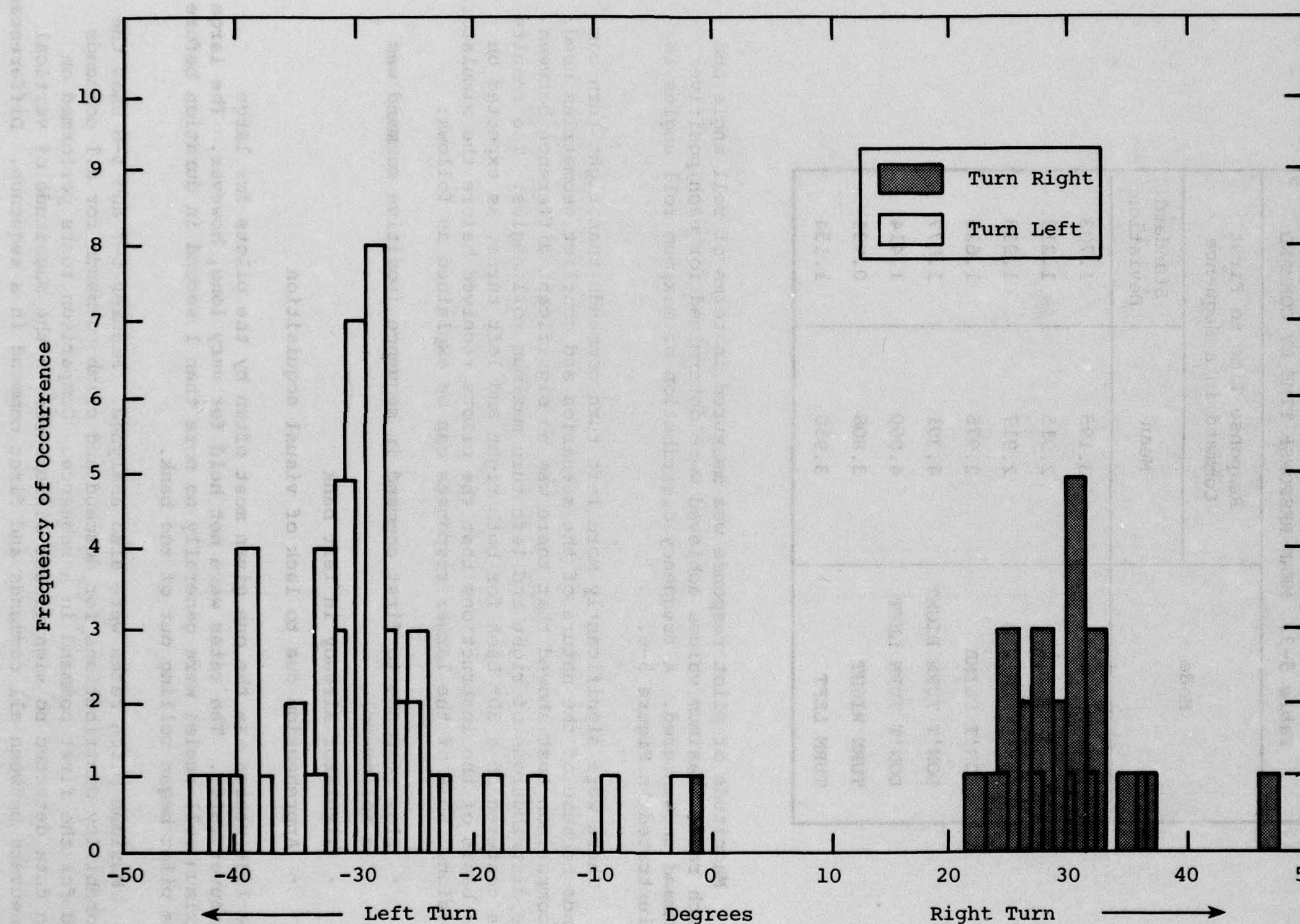
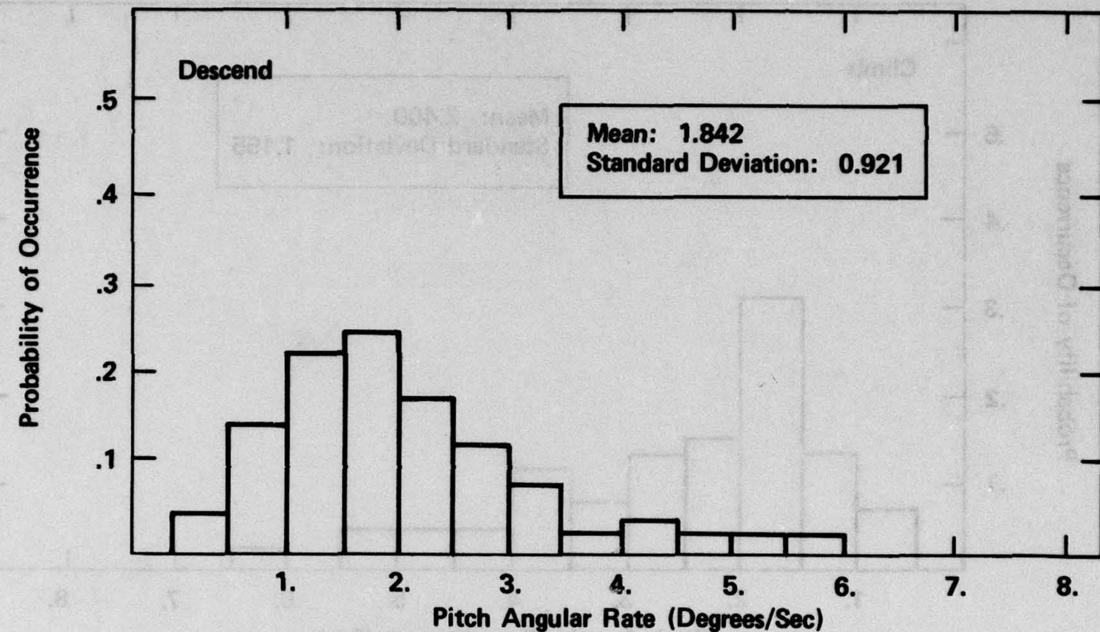
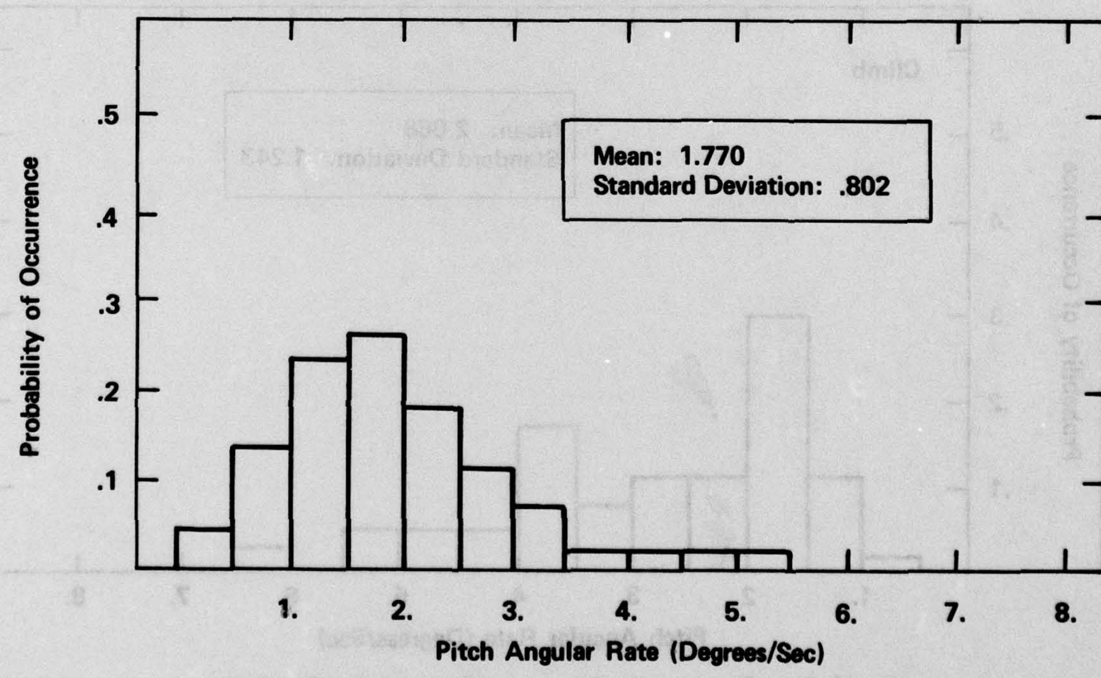


Figure 5-6. MAXIMUM ROLL ANGLE - POSITIVE HORIZONTAL COMMANDS TURN RIGHT AND TURN LEFT

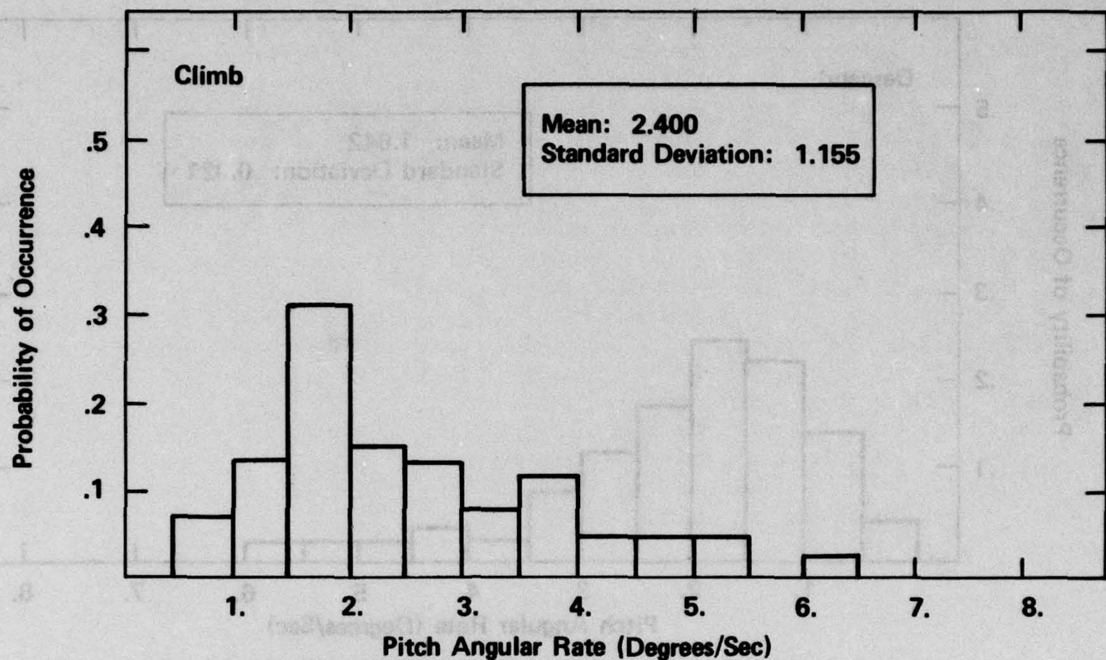


(a) All Responses to Commands Within a Conflict Series

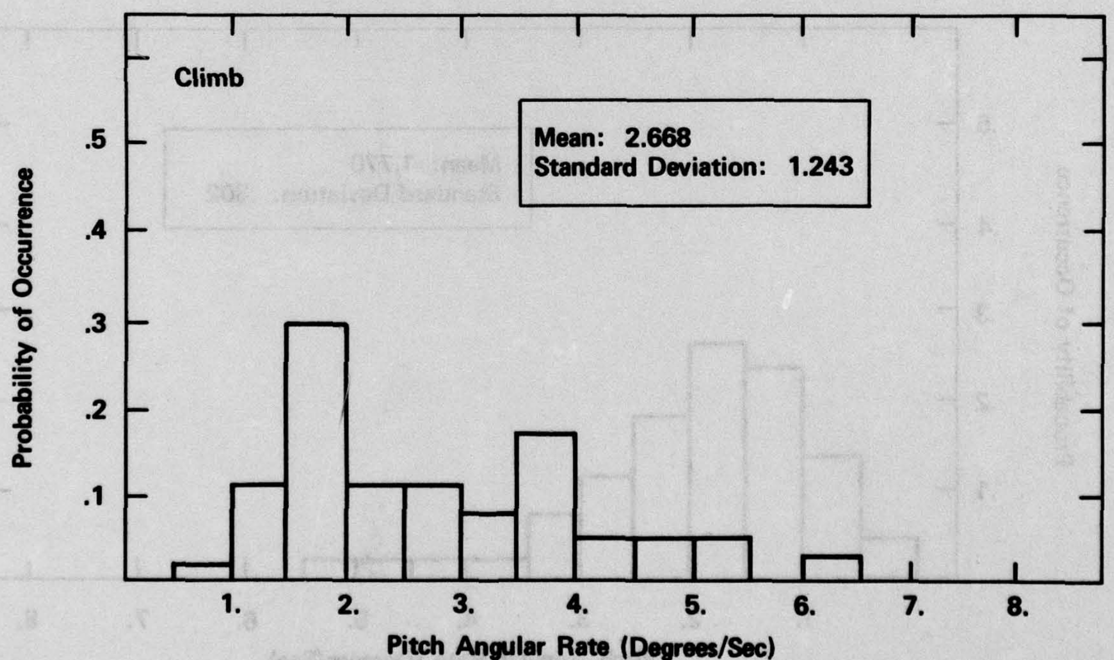


(b) First Response to Command Within a Conflict Series

Figure 5-7. PROBABILITY DISTRIBUTION, DESCEND COMMAND, MAXIMUM PITCH RATE



(a) All Responses to Commands Within a Conflict Series



(b) First Response to Command Within a Conflict Series

Figure 5-8. PROBABILITY DISTRIBUTION, CLIMB COMMAND, MAXIMUM PITCH RATE

in the mean and standard deviation for climb and descend maneuvers were investigated by using the classical F-Test and t-Test, respectively. At the 0.05 level of significance, there was a difference in pitch rate between climb and descend maneuvers; climb commands produced higher pitch rates than descend commands.

A data breakdown by display and for all command types appears in Table 5-4. Analysis shows that there are significant differences in mean maximum pitch rate for the three displays. The smallest pitch rates were associated consistently with the CRT display. This could indicate less apprehension with the conflict situation given the CRT-type presentation.

Table 5-4. MEAN MAXIMUM PITCH RATES BY COMMAND TYPE AND DISPLAY TYPE, ALL COMMANDS

Command Type	Pitch Rate (Degrees per Second) by Display Type		
	IVSI	LED	CRT
CLIMB	2.4275	2.4302	2.3283
DESCEND	1.9943	1.9608	1.5665
DON'T CLIMB	1.5584	1.4140	1.1489
DON'T DESCEND	1.6820	1.7343	1.3641
LIMIT CLIMB to 500 Feet	1.4874	1.6350	1.2177
LIMIT DESCENT to 500 Feet	1.6302	1.4490	1.0110
LIMIT CLIMB to 1,000 Feet	1.5547	2.0249	1.4028
LIMIT DESCENT to 1,000 Feet	1.5067	0.7728	1.1853
LIMIT CLIMB to 2,000 Feet	1.2596	1.9154	1.0942
LIMIT DESCENT to 2,000 Feet	1.3915	1.0798	0.9783

5.4 MISS DISTANCE ANALYSIS

This section examines the point of closest approach between conflict pairs that included the cockpit simulator. As described in Chapter Three, conflict situations were preprogrammed to occur six times in a given

scenario. This number varied because some conflicts did not materialize and others were unplanned (involving background traffic). The conflicts were designed to be "zero-zero" encounters; however, variations in the way pilots flew the simulator provided a wide range of miss distances. Some control of the intruder was available (Subsection 3.5.2), but it was used only to guarantee a displayed command. Once a command was generated, all control of the intruder ceased. This permitted the pilot to evade conflicting traffic as he would in a normal line operation.

The miss distances were recorded for 516 out of the 576 conflicts (miss distance was not recorded for the first three crews). Table 5-5 shows the breakdown of these data by display and indicates the number of close encounters that are defined as those encounters in which the achieved miss distance was less than 1/2 mile in range and 500 feet in altitude (3,079) feet slant-range). The results indicate that significantly more conflict situations developed with the IVSI than with the LED or CRT. This can be explained by the absence of traffic advisories with the IVSI. Pilots using the LED and CRT displays often used the traffic advisory information to anticipate a conflict, which generally reduced the number and duration of commands and in some cases avoided the conflict situation entirely. Another significant result was the reduction in close encounters when the CRT display was used, indicating that the pilots were able to use the display to maximize their achieved miss distance.

Figure 5-9 shows the distribution of the achieved miss distances for the close encounters. Only seven (one percent) conflict situations produced miss distances less than 500 feet slant range. The smallest miss distance was 355 feet (300 feet of which was vertical separation). The pilot was a second officer with 5,000 hours (150 hours in past year), and the small miss distance was a result of a shallow descent maneuver as a response to a DESCEND command. The same pilot responded to a CLIMB command with a shallow climb that resulted in another achieved miss distance less than 500 feet. The remaining five "near midairs" (Figure 5-9) were all in the range of 450 to 500 feet in achieved miss distance. The achieved vertical separations ranged from 160 to 430 feet.

Causes of small miss distances included the following:

- Slow response to commands
- Inadequate aircraft maneuvering
- Unfamiliarity with the United B-727 simulator
- "Tail chase" (intruder following own aircraft) conflict situations

It should be noted, however, that small miss distances (0.5 miles in range, 500 feet in altitude) occurred even when the pilots responded as instructed. On the other hand, none of these situations resulted in an unacceptable miss distance.

Another important result illustrated in Figure 5-9 is the breakdown of close encounters by display. No achieved miss distances of less than 500

Table 5-5. DISTRIBUTION OF ACHIEVED MISS DISTANCE

Conflict Statistic	Display Type			Total
	IVSI	LED	CRT	
Total Number of Miss Distance Measurements	191	160	165	516
Number of Close Encounters (< ½ Mile in Range and < 500 feet in Altitude	27	28	13	68
Percentage of Close Encounters to Total Encounters	14%	18%	8%	13%

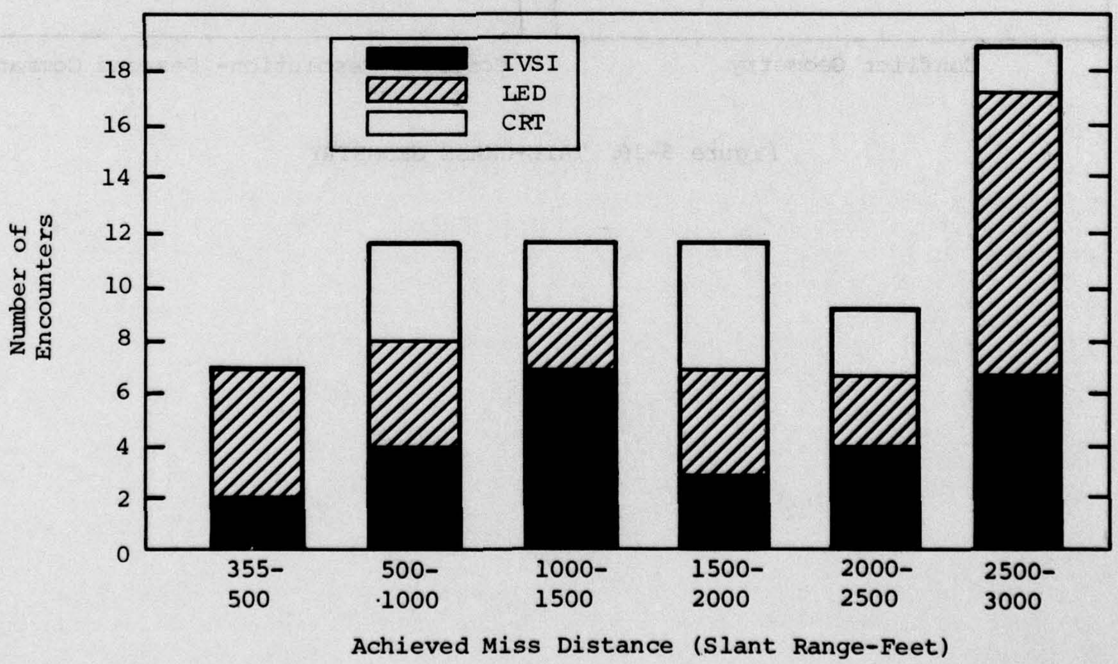


Figure 5-9. DISTRIBUTION OF MISS DISTANCES - CLOSE ENCOUNTERS

feet occurred with the CRT, and only three occurred between 500 and 1,000 feet (one was 542 feet as a result of a "tail chase," or intruder-following-own-aircraft geometry as depicted in Figure 5-10; the other two resulted in approximately 900 feet of achieved miss distance). Overall, pilots flying with the CRT (accounting for 33 percent of all flights) produced only 20 percent of the close encounters.

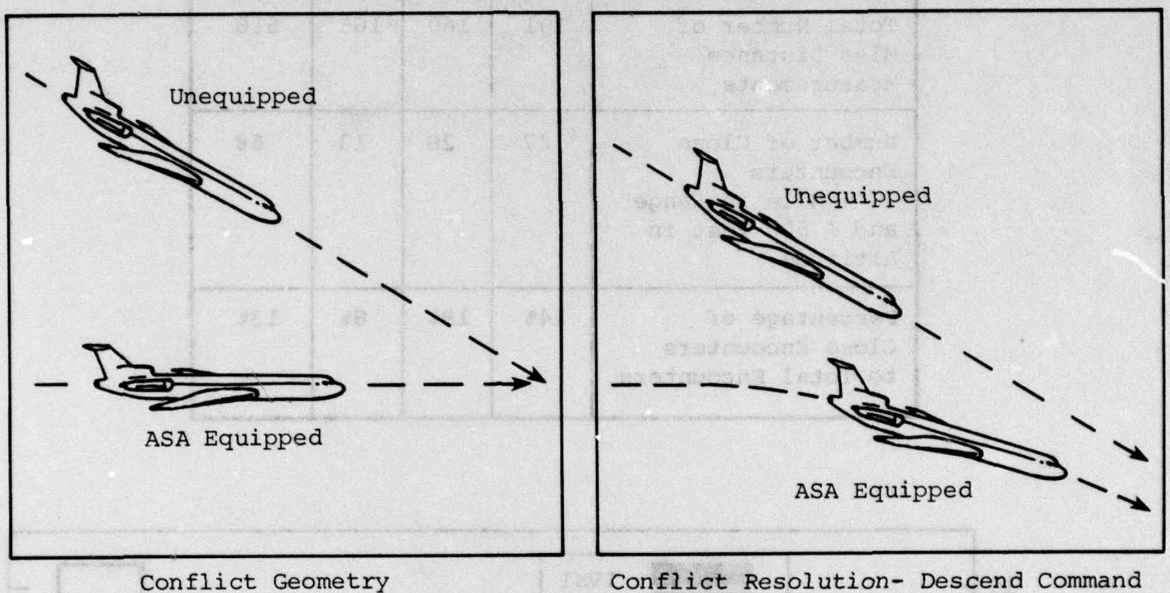


Figure 5-10. TAIL-CHASE GEOMETRY

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

This section presents conclusions based on the data analysis discussed in Chapters Four and Five. It also offers recommendations in the areas of flight testing, Aircraft Separation Assurance (ASA) logic, ASA displays, and air traffic control (ATC) and flight procedures.

6.1 CONCLUSIONS

The experimental evaluation collected both qualitative and quantitative data. The qualitative data consist of pilot opinion on ASA concepts, effectiveness, and implementation. The quantitative data provide information on pilot response to commands and effective miss distances. The conclusions are presented in the areas of display elements, display preference, display presentation, system implementation, and additional testing.

6.1.1 Display Elements

This section provides conclusions on the basic collision avoidance information elements, traffic advisories, and collision avoidance commands.

Altitude, range, relative bearing, and other aircraft heading have been identified as the most important and most essential information elements in the resolution of potential conflicts. Subject pilots feel that altitude and range alone provide sufficient information to avoid a collision. Other factors such as closure rates and angles, projected miss distance, and other aircraft vertical speed, type, and identity were considered less important data elements. Absolute (mean sea level) presentation of altitude was overwhelmingly (89 percent) favored over a relative presentation.

Most pilots (79 percent) consider traffic advisories an essential part of an ASA display. The features liked are quick reference for use in visual acquisition, constant updating of advisory information, and indication that the traffic no longer poses a threat. The pilots were able to use advisories to avoid conflicts. Advisories should be limited to

the two or three most important, with preference shown for a pictorial rather than an alphanumeric presentation.

Pilots felt that ASA commands were presented in a clear and unambiguous fashion and in sufficient time to avoid a potential collision. While the suggested maneuvers were not always what the pilots had in mind, they were generally satisfied with the results. Positive, negative, and limit commands are all considered useful commands, but there is less agreement on limit commands.

6.1.2 Display Preference

There is a definite preference for the CRT-type display presentation (alphanumeric commands with a pictorial traffic situation). The CRT was ranked first by almost 50 percent of the pilots surveyed. The LED display was ranked second and the IVSI third. A significant result, however, is that a large percentage (73 percent) of pilots surveyed would find any of the three displays acceptable. Analysis of these results by scenario, pilot experience (captains versus first officers), and recommending organization (ALPA versus airline management) indicated similar findings.

Combinations of displays were investigated; more than 50 percent of the pilots favored combining the ASA function with some other display. The IVSI and CRT combination was best received, with 26 percent of the pilots in agreement, and the IVSI and LED combination and LED and CRT combination each received 15 percent of the pilot's votes.

Alternate aircraft instruments that could be modified to provide ASA information were recommended by a third of the pilots surveyed. The instruments most often recommended were the horizontal situation indicator, the artificial horizon/flight director, and the weather radar.

6.1.3 Display Presentation

This section examines the test display evaluation and suggests those features which are most favored for a generic ASA display.

Location is a key consideration. Many of the negative comments on the LED and CRT displays related to their location on the instrument panel with respect to a normal instrument scan. Location of the IVSI probably had a significant effect on its acceptance.

Color is a very desirable feature on an ASA display for improved interpretation of the presented information, and the use of red as an indication of a positive action is acceptable.

An aural alerting feature is considered a necessary evil. Most pilots felt that an aural alert was required; however, there were strong warnings against a "startling alarm."

Character size and symbolic presentation are also important factors. Pilots want easy readability of alphanumeric text and consider arrows to provide the best presentation of positive commands. In addition, too many alphanumerics reduce readability; unnecessary text should be eliminated.

6.1.4 System Implementation

This section examines the issues of ASA maneuvers, system effectiveness, the impact of ASA introduction on ATC and flight procedures, and additional testing.

The introduction of ASA to the flight deck has added what pilots consider an acceptable increase in workload for the nonflying pilot. More voice communication is expected unless the ASA commands can be electronically transmitted to the air traffic controller. Additional voice communication may also occur, initially, to verify traffic that appears on the ASA display but is not visually acquired.

Pilots are concerned about maneuvering into other aircraft as a result of an ASA command. This is one of the main reasons for interest in displayed traffic advisories, and a reason given for preference of horizontal commands over vertical. This preference is not shared by all pilots, however. While horizontal maneuvers are generally preferred for takeoff, approach, or landing phases, there was no strong preference for either horizontal or vertical maneuvers *during other phases* of flight. The pilots who preferred horizontal maneuvers cited passenger comfort and safety as a key consideration in maneuvering the aircraft. Horizontal maneuvers provide a guaranteed positive G load and less passenger anxiety, seldom require power changes, are generally unaffected by gear and flap configurations, and are independent of terrain problems. Pilots favoring vertical maneuvers cited more maneuvering room, easier response, and more rapid flight path change (at most speeds).

Response to commands was somewhat faster for vertical versus horizontal maneuvers, but the difference was only 1 second, which does not have a major impact on the system design. Average response time ranged from 3 to 3.5 seconds. The IVSI, which was the least complex and most "in scan" instrument, provided the quickest response; and the CRT, which was the most complex and farthest "out of scan" instrument, provided the slowest response. The response time was defined as the time from command presentation to maneuver initiation and was measured to 1-second accuracy. Response to commands was not excessive in either the vertical or horizontal dimension and was not perceived by the pilots as excessive.

Pilots expressed increased confidence while flying with ASA but not enough to permit reducing lateral separation standards. Concern was expressed about unnecessary alarms, but this was not considered a problem if pilots were provided supporting information as to why the alarm went off. Pilots were concerned about system reliability, however. They felt that the system must work all of the time or it would be ignored by the pilot.

The system was effective in producing a 500-foot slant range miss distance in 99 percent of the conflict situations. In some of these "close" situations, the pilots were unfamiliar with the aircraft or less experienced. The resolution logic was least effective in a "tail chase" geometry, where an intruder aircraft was descending on top of the simulator and only vertical maneuvers were available for resolution (active mode). The number of "close" situations decreased inversely to the amount of supporting information on the display, and none of these situations occurred while the CRT display was in use. In fact, the total number of conflicts was significantly higher with the IVSI because of a lack of supporting information (traffic advisories).

Other criticism of the resolution logic reflected dissatisfaction in the updating of limit vertical commands. The current logic allows vertical limit commands to be changed as often as once per second in active mode. This rate is perceived as too rapid, and it causes confusion. Positive and negative commands had to be displayed for 5 seconds before being updated. The pilots were more comfortable with the 5-second rate.

Pilots felt that few or no changes would be required in flight procedures. Those who suggested changes saw added duties for the nonflying pilot (monitoring the ASA display), a requirement to equip aircraft with transponders, and, potentially, changes to the nominal instrument scan.

Changes to ATC procedures centered primarily on the problem of unexpected deviations caused by ASA maneuvers. Pilots foresee the requirement of immediate notification of flight path deviations to the air traffic controller. Some traffic advisories may have to be issued by ATC to prevent unnecessary maneuvering, while others might be eliminated. Separation standards might have to be increased in terminal areas because of unanticipated deviations and may be reduced in other areas.

While pilots wanted the system "yesterday," most believed that additional testing was required. They suggested flight tests, and those who specified the type of testing recommended line operation testing.

6.2 RECOMMENDATIONS

6.2.1 Flight Test

It is recommended that consideration be given to both operational and experimental flight tests. The ASA logic should be subjected to flight testing in an actual airline operational environment to achieve the following objectives:

- Determine the incidence of ASA alarms
- Determine the incidence of false ASA alarms
- Establish the sensitivity of ASA performance to aircraft density

Identify pilot reactions to ASA commands in actual flight conditions

Experimental flight tests should be conducted by the FAA to stress the ASA logic and determine the satisfactory operation and reliability of the experimental ASA equipment.

6.2.2 ASA Logic Modifications

It is recommended that the ASA logic be modified to provide the same minimum display time for limit commands as provided for positive and negative commands. In addition, specific geometries, such as the "tail chase" geometry, should be further investigated to determine if the situation might be improved by procedural instructions.

6.2.3 ASA Displays

The design and selection of the best ASA display is dependent on the aircraft's normal operational environment and should be determined by the aircraft operator. Specific consideration should be given to display location, use of color, inclusion of traffic advisories, symbolic representation of information, and combined function displays (normal instrument function plus ASA).

6.2.4 ATC and Flight Procedures

Before implementation of an ASA system, a set of operational procedures should be developed in the areas of response to ASA traffic advisories, response to ASA commands, and communication with ATC during a conflict situation. A training program should be established to explain how the system functions, what each type of command advisory represents in terms of a traffic situation, and the command sequences that might be produced. Normally, the development of pilot training programs and flight procedures is the responsibility of the aircraft operator, subject to the approval of the FAA. It is expected that pilot procedures will be developed by a committee composed of airline industry personnel and approved by the Federal Aviation Administration.